Role of the Nucleus-Nucleus Potential in Sub-barrier Fusion

Şerban Mişicu

NIPNE-HH, Bucharest

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Nuclear Physics – Presence and Future

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Role of the Nucleus-Nucleus Potential in Sub-barrier Fusion

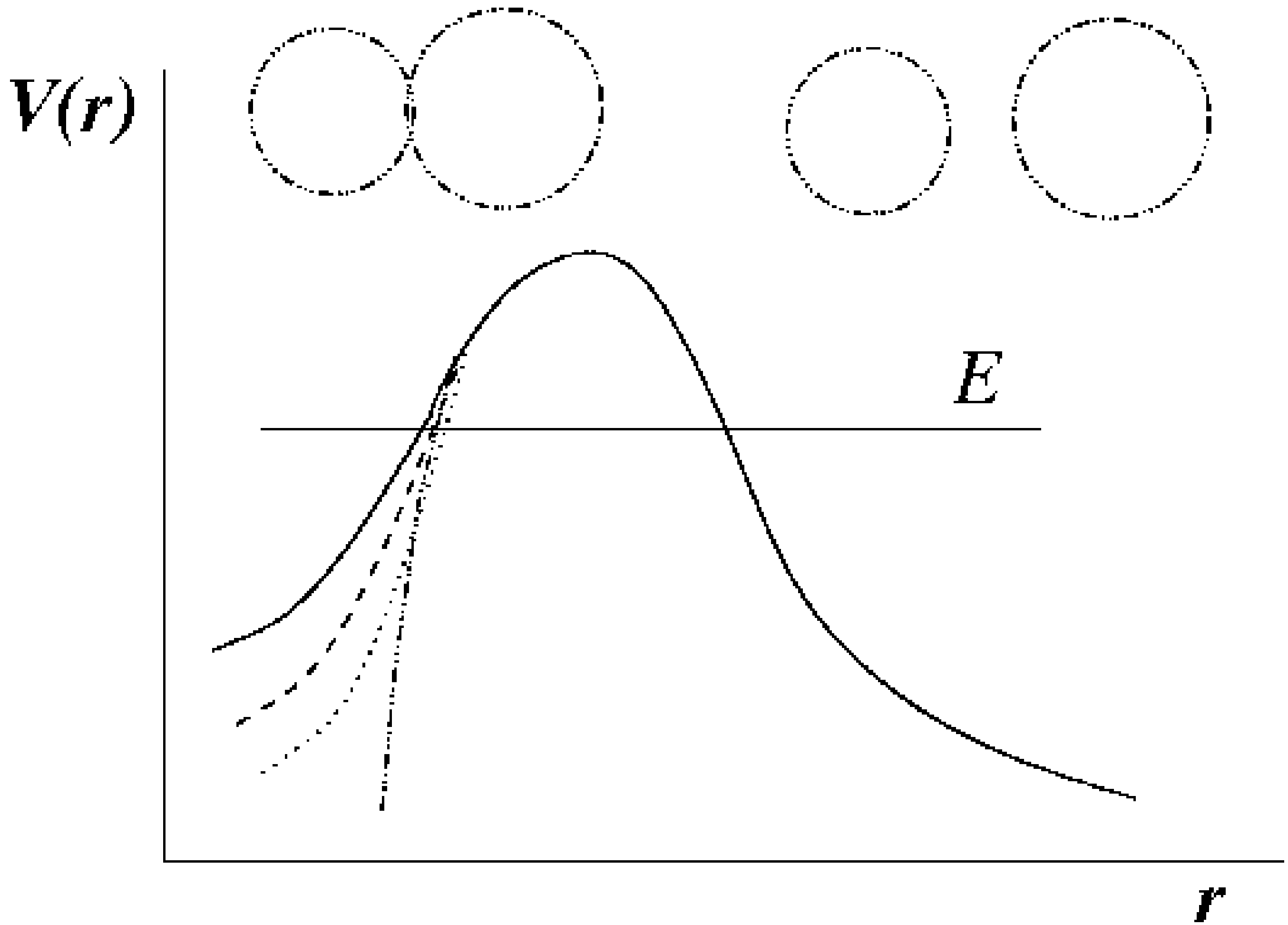
* Introductory remarks

* Nucleus-Nucleus Potential :
  - *Nucleon-Nucleon interaction*
  - *Orientation*

* Sub-barrier Fusion
  - *Capture Reactions with ^{48}Ca projectile*
  - *Hindrance to fusion deep under the barrier*

SUB-BARRIER FUSION

- Formation of the compound nucleus through the quantum tunneling of the Coulomb barrier of two nuclei ($E<B_c$)



SUB-BARRIER FUSION : Introductory remarks

- Test the nuclear potential inside the barrier

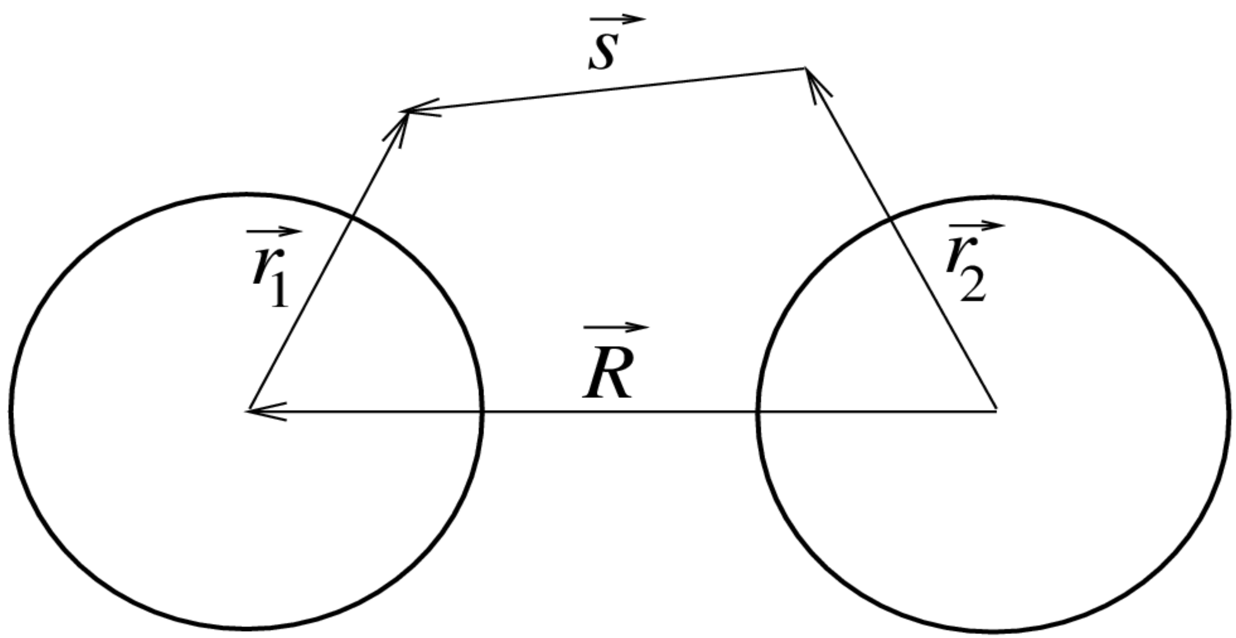
- Enhancement of cross-sections due to nuclear structure :
  vibrational nuclei(sensitivity to multi-phonon excitations) ,
  rotational excitations (effect of higher multipole defomations)

- Gate to the synthesis of heavy and superheavy nuclei

- Burning Cycles (C & O) in massive stars – extrapolation of near-barrier data on σ_F of C and O reactions down to astrophysical energies

Double folding Heavy Ion Potential

$$V_{DF}(\boldsymbol{R}) = \int d\boldsymbol{r}_1 d\boldsymbol{r_2} \rho(\boldsymbol{r_1})\rho(\boldsymbol{r_2}) v(\boldsymbol{r}_1 + \boldsymbol{R} - \boldsymbol{r_2}) = (\rho_1 * (\rho_2 * v))$$



Double folding Heavy Ion Potential

$$V_{DF}(\boldsymbol{R}) = \int d\boldsymbol{r}_1 d\boldsymbol{r_2} \rho(\boldsymbol{r_1})\rho(\boldsymbol{r_2}) v(\boldsymbol{r}_1 + \boldsymbol{R} - \boldsymbol{r_2}) = (\rho_1 * (\rho_2 * v))$$

Ground state one-body densities(spherical):

M3Y	:	Fermi-Dirac with FRLDM parameters
Skyrme	:	HFBRAD
Gogny	:	HFB

Ground state one-body densities(deformed):

$$\rho(\boldsymbol{r}) = \rho_0 \left[1 + \exp \frac{1}{a} \left(r - R_0 \left(1 + \sum_{\lambda=2,3,4} \beta_\lambda Y_{\lambda 0}(\theta, 0) \right) \right) \right]^{-1}$$

Double folding Heavy Ion Potential

$$V_{\rm DF}(\boldsymbol{R}) = \int d\boldsymbol{r}_1 d\boldsymbol{r}_2 \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2) v((\boldsymbol{r}_1 + \boldsymbol{R} - \boldsymbol{r}_2) \equiv \rho_1 * \rho_2 * v$$

central part of the effective $N-N$ interactions may be written as

$$v = v_{00}(\boldsymbol{r}) + v_{01}(\boldsymbol{r})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) + v_{10}(\boldsymbol{r})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) + v_{11}(\boldsymbol{r})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$$

(σ,τ) representation

From the exceedingly large number of exchange terms retain only the knock-on (KOE) term :
two nucleons are interacting and in the same time are exchanged

$$v = v^{\rm d}(\boldsymbol{r}, \rho) + v^{\rm ex}(\boldsymbol{r}, \rho) P_{12}^{x}$$

$$v^{\rm d} = \sum_{S,T} v_{S,T} P_s^{\sigma} P_s^{\tau}, \quad v^{\rm ex} = \sum_{S,T} (-)^{S+T+1} v_{S,T} P_s^{\sigma} P_s^{\tau},$$

G-matrix interactions

G-matrix elements of a bare *NN* interaction in an oscillator basis were obtained solving Bethe-Goldstone equation and then fitted with a sum of Yukawa f.f.

$$v(r) = \sum_{i=1}^{n_{max}} V_i \frac{\exp(-\mu_i r)}{\mu_i r}$$

(I)   M3Y-Reid (standard)   [Bertsch et al., NPA 284, 399 (1977)]

(ii) M3Y-Paris   [Antaraman,Toki and Bertsch, NPA 398, 269 (1978)]

(iii) M4Y-Paris   [Hosaka,Kubo,Toki, NPA 444, 76 (1985)]

G-matrix interactions are local and purely real. Density dependence is implicit through the oscillator parameter and it is characteristic to $\approx\rho_{NM}/3$

Density-dependent effective interactions

Gogny interaction : a sum of central, finite-range term and a zero-range d.d. Term

neglect spin-orbit term for spin-saturated nuclei

$$v(\boldsymbol{r}_{12}) = \sum_{i=1}^{2} (W_i + B_i P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) e^{-\frac{r_{12}^2}{\mu_i^2}} + t_3 (1 + P^\sigma) \rho^\alpha \left(\frac{\boldsymbol{r}_1 + \boldsymbol{r}_2}{2} \right) \delta(\boldsymbol{r}_{12})$$

(σ, τ) representation

$$v_{00}^{\mathrm{d}} = \frac{1}{4} \sum_{i=1}^{2} (4W_i + 2B_i - 2H_i - M_i) e^{-\frac{r_{12}^2}{\mu_i^2}} + \frac{3}{2} t_3 \rho^\alpha \left(\frac{\boldsymbol{r}_1 + \boldsymbol{r}_2}{2} \right) \delta(\boldsymbol{r}_{12})$$

$$v_{00}^{\mathrm{ex}} = -\frac{1}{4} \sum_{i=1}^{2} (W_i + 2B_i - 2H_i - 4M_i) e^{-\frac{r_{12}^2}{\mu_i^2}} - \frac{3}{4} t_3 \rho^\alpha \delta(\boldsymbol{r}_{12})$$

Density-dependent effective interactions

Skyrme interaction : a sum of a zero-range local, non-local and d.d. terms

$$
\begin{aligned}
v(\boldsymbol{r}_{12}) &= t_0(1+x_0P_\sigma)\delta(\boldsymbol{r}_{12}) \\
&+ \frac{1}{2}t_1(1+x_1P_\sigma)\left(\boldsymbol{p}^{\dagger 2}\delta(\boldsymbol{r}_{12})+\delta(\boldsymbol{r}_{12})\boldsymbol{p}^2\right)+t_2(1+x_2P_\sigma)\boldsymbol{p}^\dagger\cdot\delta(\boldsymbol{r}_{12})\boldsymbol{p} \\
&+ \frac{1}{6}t_3(1+x_3P_\sigma)\left[\rho\left(\frac{\boldsymbol{r}_1+\boldsymbol{r}_2}{2}\right)\right]^\alpha\delta(\boldsymbol{r}_{12})+iW_0\boldsymbol{\sigma}\cdot[\boldsymbol{p}^\dagger\times\delta(\boldsymbol{r}_{12})\boldsymbol{p}]
\end{aligned}
$$

(σ,τ) representation

$$
\begin{aligned}
v_{00}^{\mathrm{d}} = &\quad t_0(1+\frac{1}{2}x_0)\delta(\boldsymbol{r})+\frac{1}{6}t_3(1+\frac{1}{2}x_3)[\rho(\boldsymbol{R})]^\alpha\delta(\boldsymbol{r}) \\
&+ \frac{1}{2}t_1(1+\frac{1}{2}x_1)\left(\boldsymbol{p}^{\dagger 2}\delta(\boldsymbol{r})+\delta(\boldsymbol{r})\boldsymbol{p}^2\right)+t_2(1+\frac{1}{2}x_2)\boldsymbol{p}^\dagger\cdot\delta(\boldsymbol{r})\boldsymbol{p} \\
v_{00}^{\mathrm{ex}} = &- \frac{1}{4}t_0(1+2x_0)\delta(\boldsymbol{r}) \\
&- \frac{1}{8}t_1(1+2x_1)\left(\boldsymbol{p}^{\dagger 2}\delta(\boldsymbol{r})+\delta(\boldsymbol{r})\boldsymbol{p}^2\right)-\frac{1}{4}t_2(1+2x_2)\boldsymbol{p}^\dagger\cdot\delta(\boldsymbol{r})\boldsymbol{p} \\
&- \frac{1}{24}t_3(1+2x_3)[\rho(\boldsymbol{R})]^\alpha\delta(\boldsymbol{r})
\end{aligned}
$$

Exchange Kernels (finding a local equivalent)

Pseudopotential approximation : $v_{ex}P_{12}^{x} \longrightarrow f(\rho_0, K)\delta(\vec{s})$

$$U_L(R) = f(\rho_0, K_0/\mu)\int \rho_1(r_1)\rho_2(r_2)\delta(\boldsymbol{R}+\boldsymbol{r}_1-\boldsymbol{r}_2)d\boldsymbol{r}_1 d\boldsymbol{r}_2$$

$$f(\rho_0, K) = 4\pi\int v_{ex}(s)\hat{j}_1^2(\hat{k}(\rho_0))j_0(Ks)s^2 ds$$

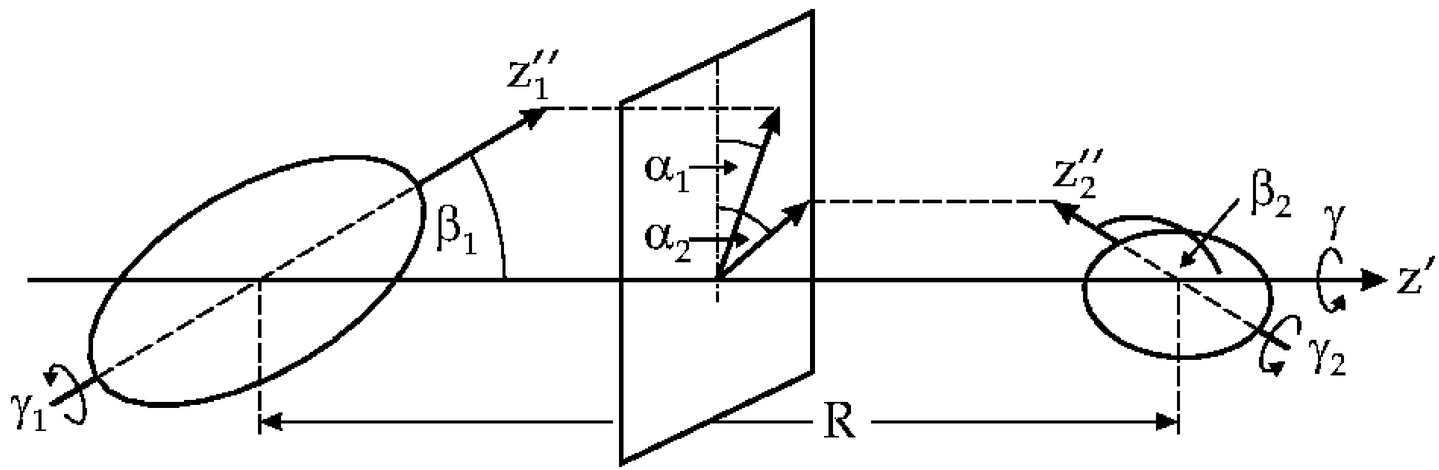
Energy dependence

Perey-Saxon localization procedure:

$$U_L(R) = 4\pi\int d\vec{x}\rho_1(x)\rho_2(|\vec{R}-\vec{x}|)\int s^2 ds v_{ex}(s)\hat{j}_1(k_{f1}(x)\frac{A_1-1}{A_1}s)\hat{j}_1(k_{f2}(|\vec{R}-\vec{x}|)\frac{A_2-1}{A_2}s)j_0(\frac{K(R)s}{\mu})$$

Full recoil included

Orientation



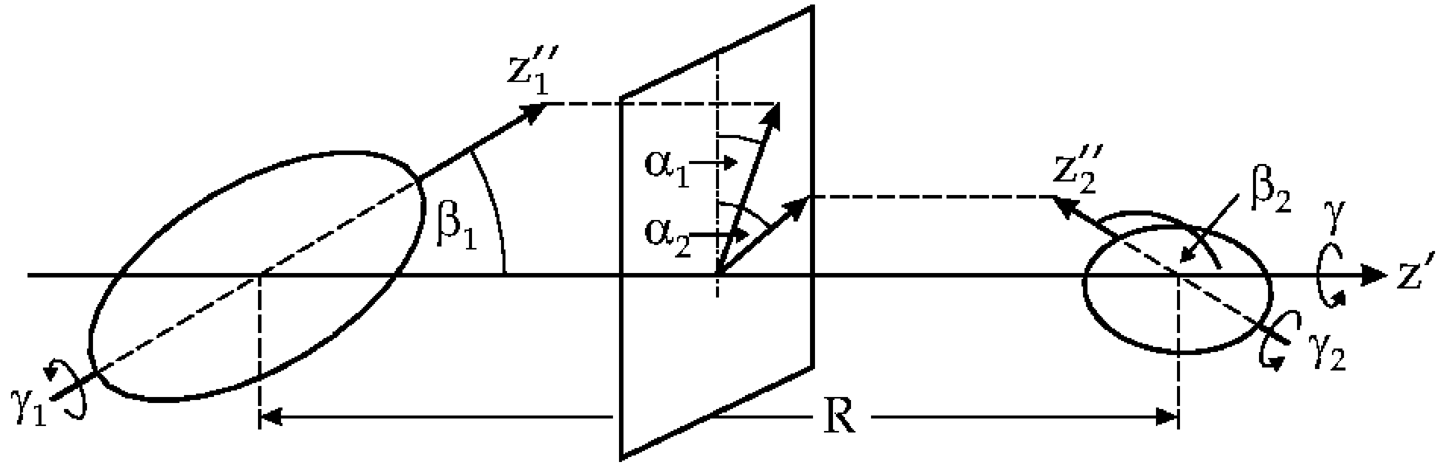
$$\omega_i = (\alpha_i, \beta_i, \gamma_i)$$

$$V_{DF}(\boldsymbol{R}) = \frac{1}{(2\pi)^3} \int d\boldsymbol{q} \widetilde{V}(\boldsymbol{q}) \exp(-i\boldsymbol{q} \cdot \boldsymbol{R})$$

$$\widetilde{V}(\boldsymbol{q}) = \widetilde{\rho}_1(\boldsymbol{q}) \widetilde{\rho}_2(-\boldsymbol{q}) \widetilde{v}(\boldsymbol{q})$$

$$\rho_i(\boldsymbol{r}') = \mathcal{R}(\alpha_i, \beta_i, \gamma_i) \rho_i(\boldsymbol{r}'') \qquad \rho_i(\boldsymbol{r}'') = \sum_{\lambda} \rho_\lambda(\boldsymbol{r}'') Y_{\lambda 0}(\hat{r}'')$$

Orientation



$$\omega_i = (\alpha_i, \beta_i, \gamma_i)$$

$$V(\boldsymbol{R}) = \sum V^{\mu_1\ \mu_2\ \mu_3}_{\lambda_1\ \lambda_2\ \lambda_3}(R) D^{\lambda_1}_{\mu_1 0}(\omega_1) D^{\lambda_2}_{\mu_2 0}(\omega_2) D^{\lambda_3}_{\mu_3 0}(\Phi, \Theta, 0)$$

$$V^{\ \mu_1\ \mu_2\ \mu_3}_{\ \lambda_1\ \lambda_2\ \lambda_3}(R) = \frac{1}{(2\pi)^3} i^{\lambda_1 - \lambda_2 - \lambda_3} \hat{\lambda}_1 \hat{\lambda}_2 \hat{\lambda}_3^2 \begin{pmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} \lambda_1 & \lambda_2 & \lambda_3 \\ \mu_1 & \mu_2 & \mu_3 \end{pmatrix} F_{\lambda_1 \lambda_2 \lambda_3}(R)$$

Fixed Molecular Axis

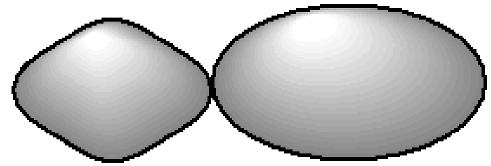
$$V(\boldsymbol{R}) = \sum_{\lambda_i \mu} V^{\ \mu - \mu\ \ 0}_{\ \lambda_1\ \lambda_2\ \lambda_3}(R) \cos \mu(\alpha_2 - \alpha_1) d^{\lambda_1}_{\mu 0}(\beta_1) d^{\ \lambda_2}_{-\mu 0}(\beta_2)$$

Orientation

Touching Configurations

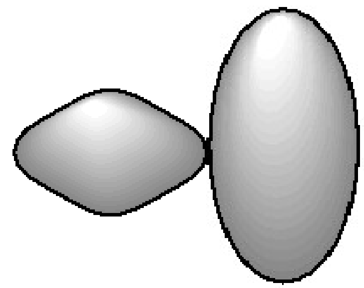
(i) Pole-Pole(nose-to-nose)

$$\alpha_1 = \alpha_2 = 0 \ , \beta_1 = \beta_2 = 0$$



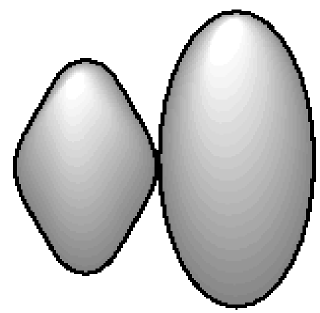
(ii) Pole-Equator(nose-to-bely)

$$\alpha_1 - \alpha_2 = 0, \ \beta_1 = 0 \text{ and } \beta_2 = \frac{\pi}{2}$$



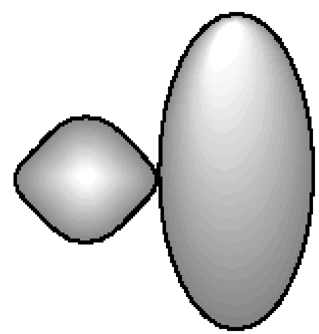
(iii) Equator-Equator(belly-to-bely)

$$\alpha_1 - \alpha_2 = 0, \beta_1 = \beta_2 = \frac{\pi}{2}$$



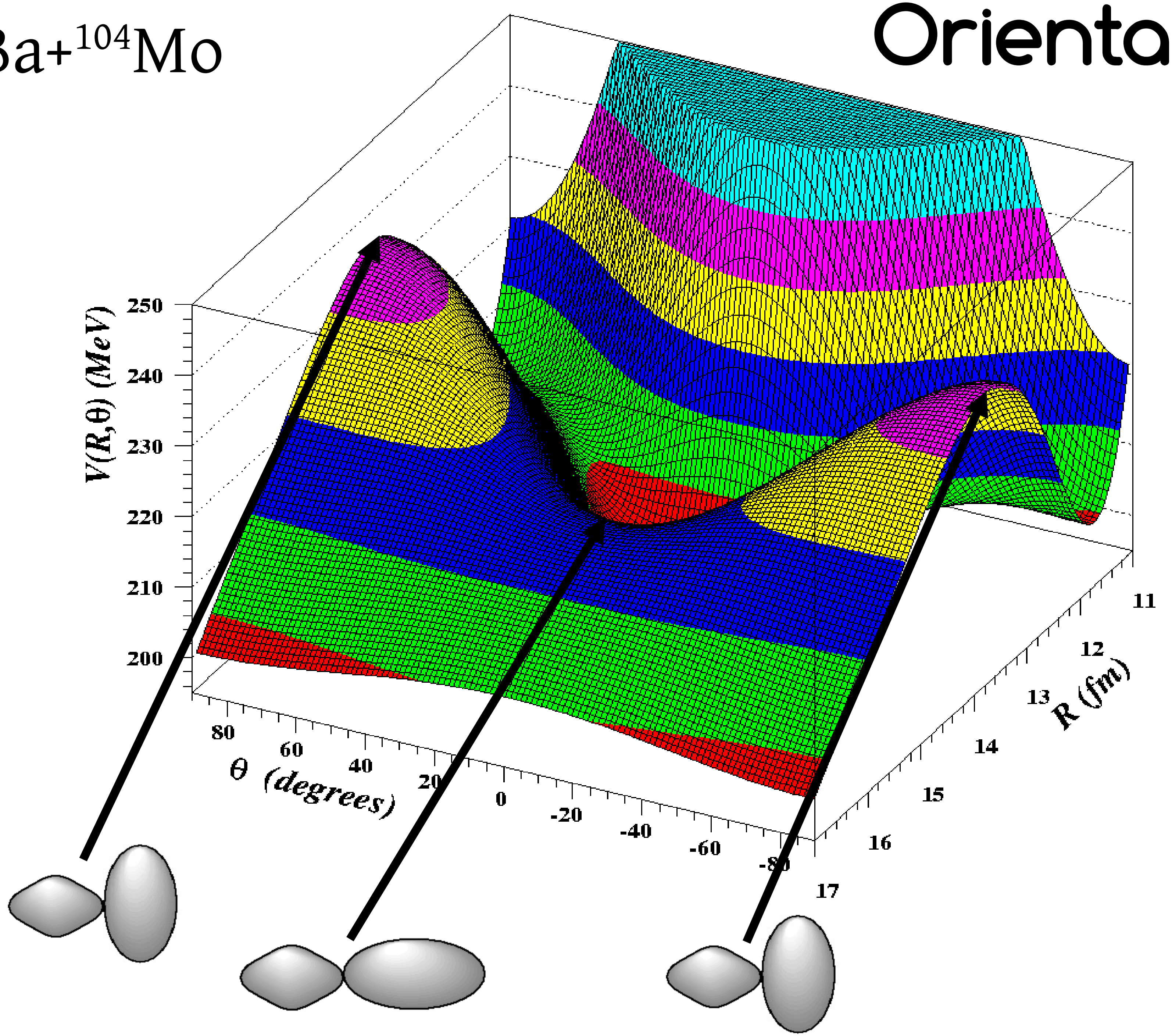
(iv) Equator-Equator Twisted(crossed bellies)

$$\alpha_1 - \alpha_2 = \frac{\pi}{2}, \beta_1 = \beta_2 = \frac{\pi}{2}$$



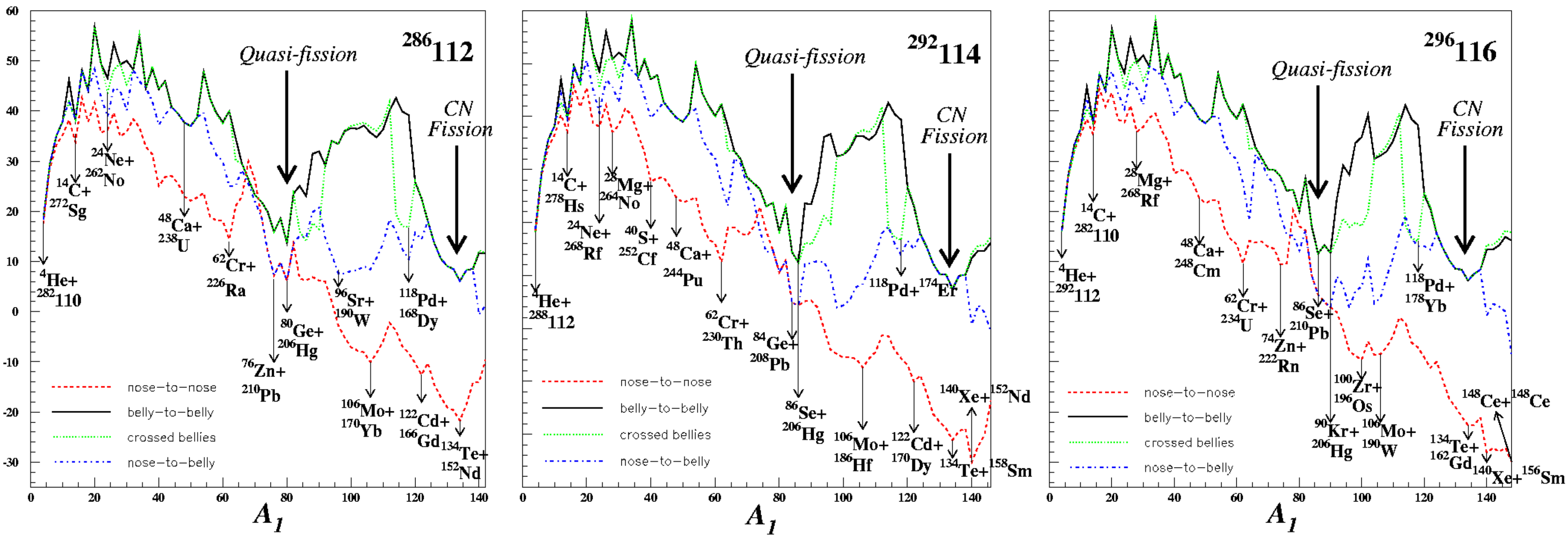
$^{148}Ba+^{104}Mo$

Orientation



Ş.Mişicu&W.Greiner, JPG 28, 2861 (2002).

Capture Reactions with ^{48}Ca projectile



Ş.Mişicu&W.Greiner, PRC 66, 044606 (2002).

Coupling with Rotational Band States

$$H = T + H_{\rm rot}(\omega) + V(R,\omega)$$

$$\Psi(\boldsymbol{R},\omega) = \sum_{JM} a_{JM}\psi_{JM}(\boldsymbol{R},\omega)$$

$$\psi_{JM}(\boldsymbol{R},\omega) = \mathcal{R}_{JIl}(R)\Phi_{JMIl}(R,\omega) + \sum_{I'l'}\mathcal{R}_{JI'l'}(R)\Phi_{JMI'l'}(R,\omega)$$

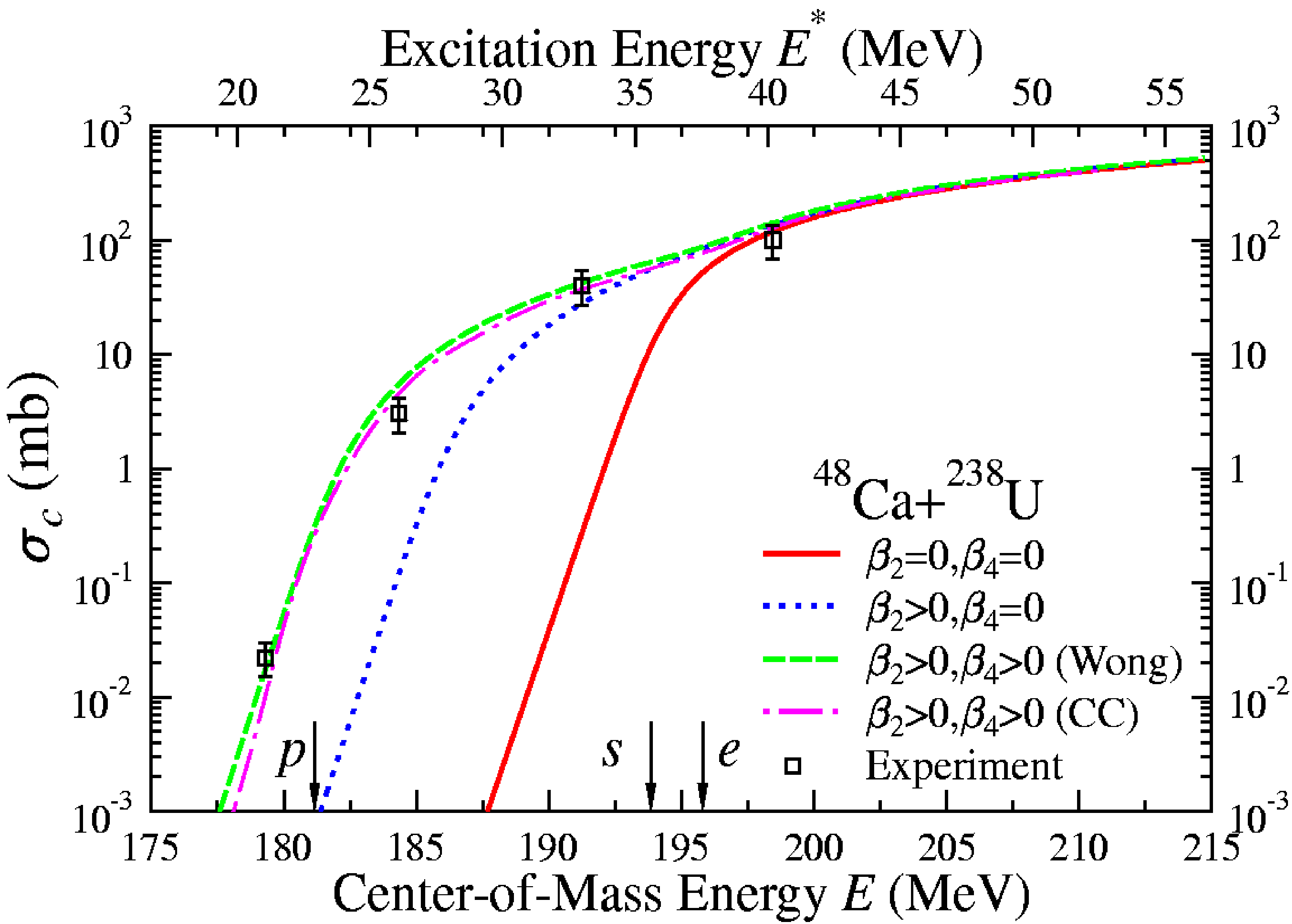
$$\left\{-\frac{\hbar^2}{2\mu}\left(\frac{\partial^2}{\partial R^2} - \frac{l(l+1)}{R^2}\right) + \varepsilon_I - E\right\}\mathcal{R}_{JIl}(R) + \sum_{I'l'}\mathcal{R}_{JI'l'}(R)\langle\Phi_{JMIl}|V(R,\omega)|\Phi_{JMI'l'}\rangle = 0$$

$$\langle\Phi_{JMIl}|V(R,\omega)|\Phi_{JMI'l'}\rangle = (-)^{l+I}\hat{I}\hat{I}'\hat{l}\hat{l}'\sum_{\lambda}\begin{pmatrix} I & I' & \lambda \\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix} l & \lambda & l' \\ 0 & 0 & 0\end{pmatrix}\begin{Bmatrix} l & I & J \\ I' & l' & \lambda\end{Bmatrix} V^{\,0\;0\;0}_{\,\lambda\;0\;\lambda}(R)$$

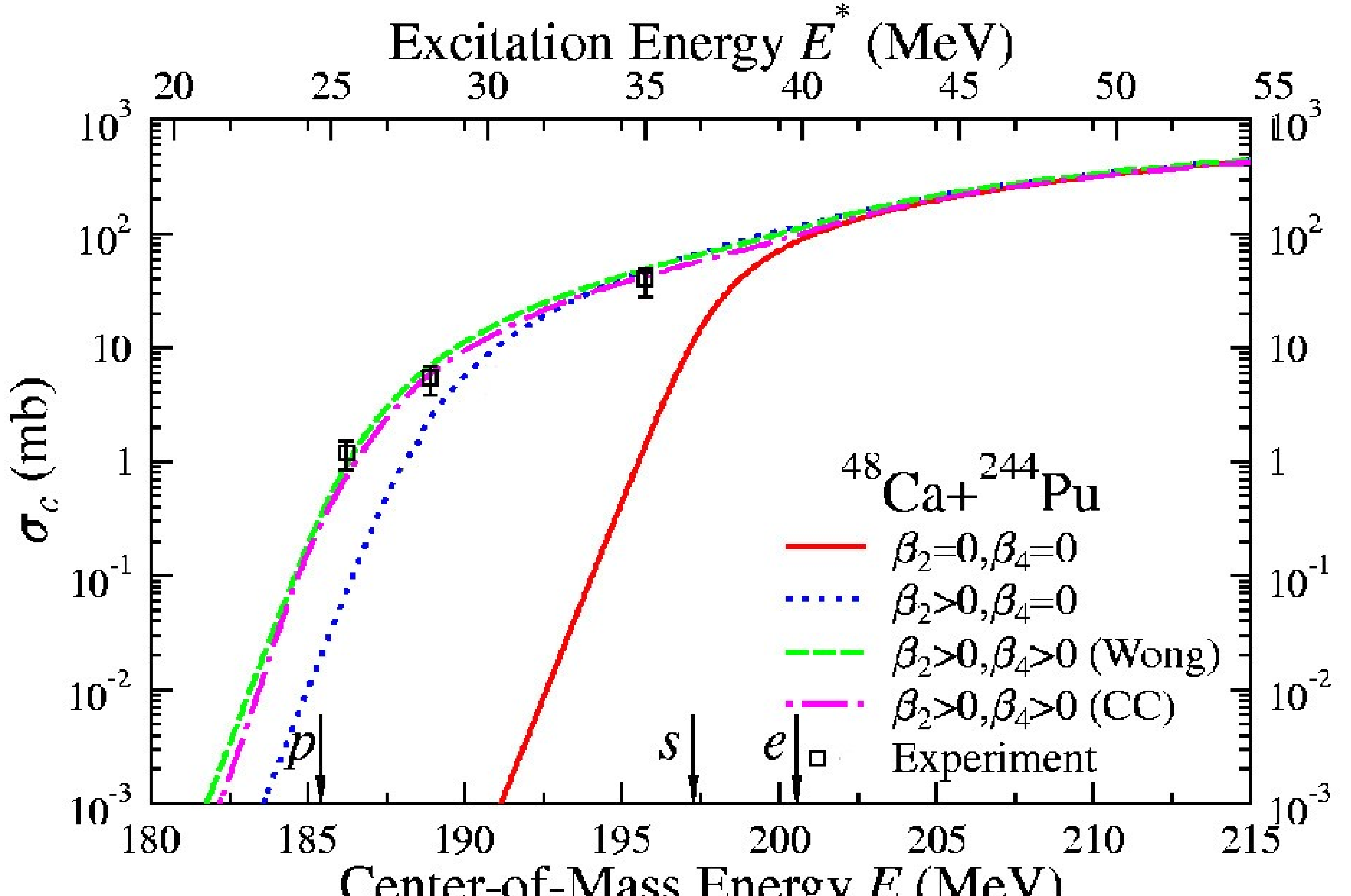
$$\psi_{IJ} = \sum_{l}\sqrt{2l+1}\begin{pmatrix} l & \lambda & l' \\ 0 & 0 & 0\end{pmatrix}\mathcal{R}_{JIl}(R)$$

$$\left\{-\frac{\hbar^2}{2\mu}\left(\frac{\partial^2}{\partial R^2} - \frac{J(J+1)}{R^2}\right) + \varepsilon_I - E\right\}\psi_{IJ} + \sum_{I'}\hat{I}\hat{I}'\sum_{\lambda}V^{\,0\;0\;0}_{\,\lambda\;0\;\lambda}(R)\begin{pmatrix} I & \lambda & I' \\ 0 & 0 & 0\end{pmatrix}^2\psi_{I'J} = 0$$

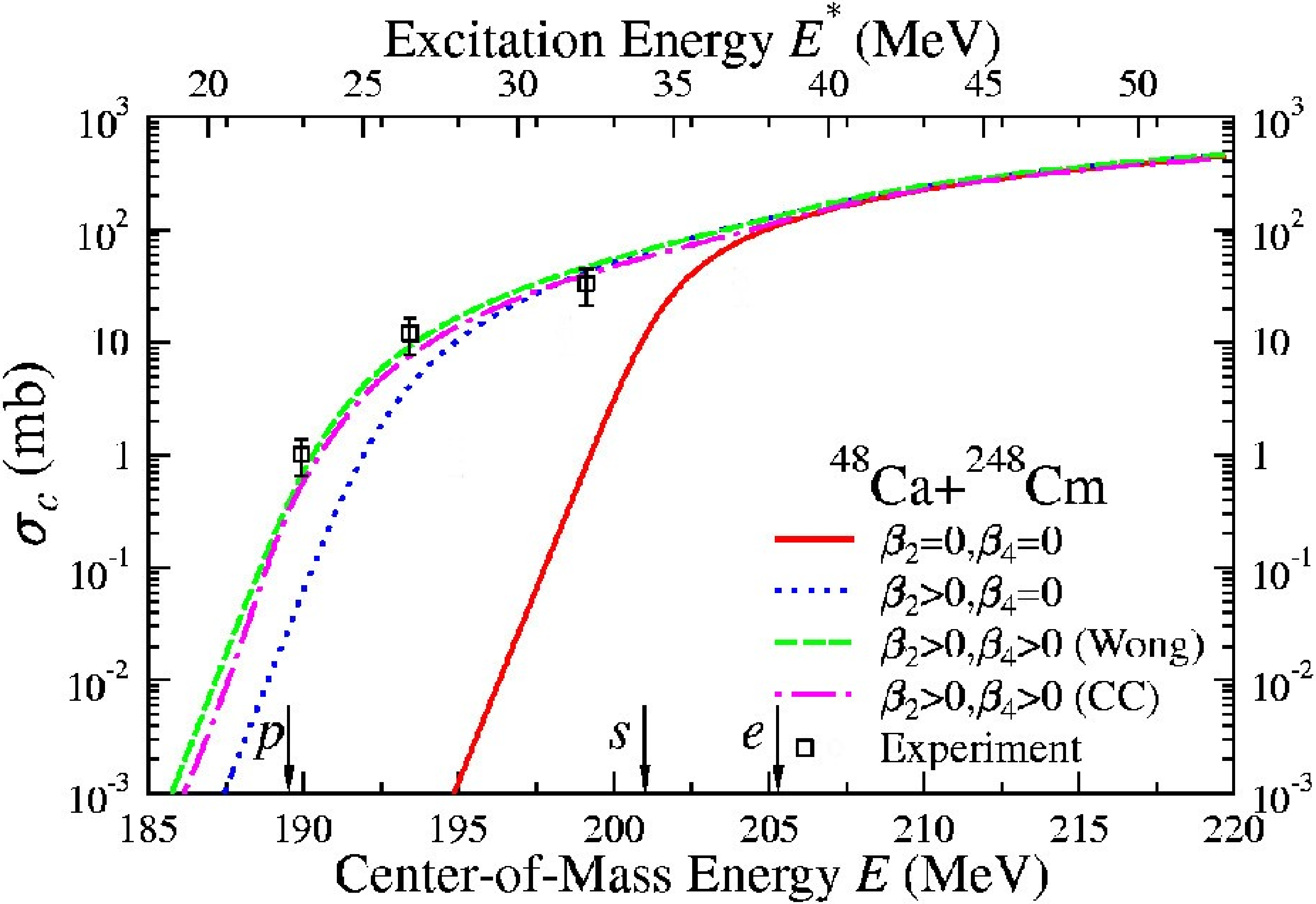
$$\sigma_c(E) = \frac{\pi}{k^2}\sum_{l}(2J+1)P_J(\theta)$$



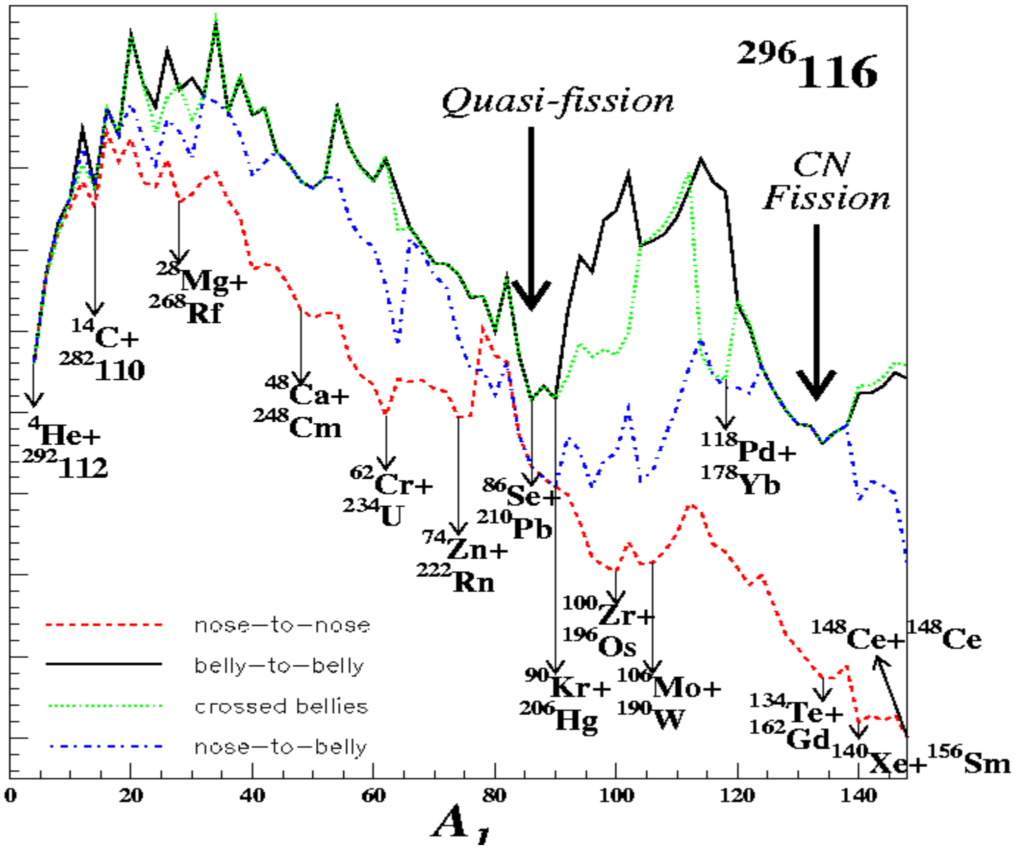
Ş.Mişicu&W.Greiner, PRC 69, 054601 (2004).



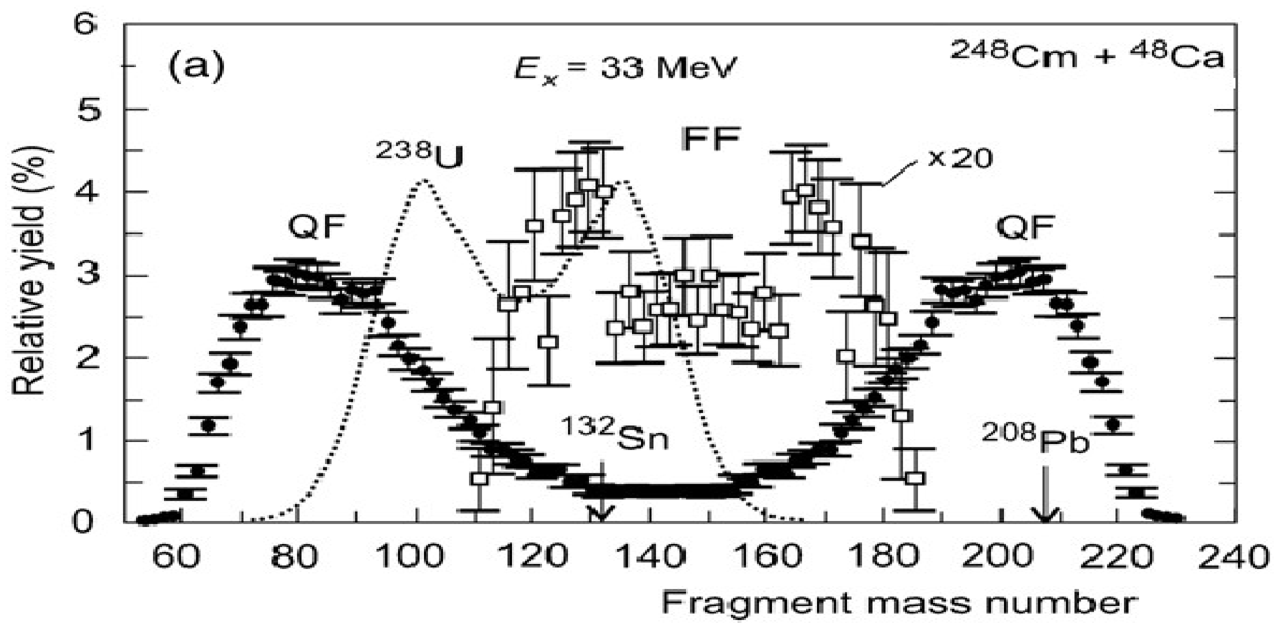
Ş.Mişicu&W.Greiner, PRC 69, 054601 (2004).



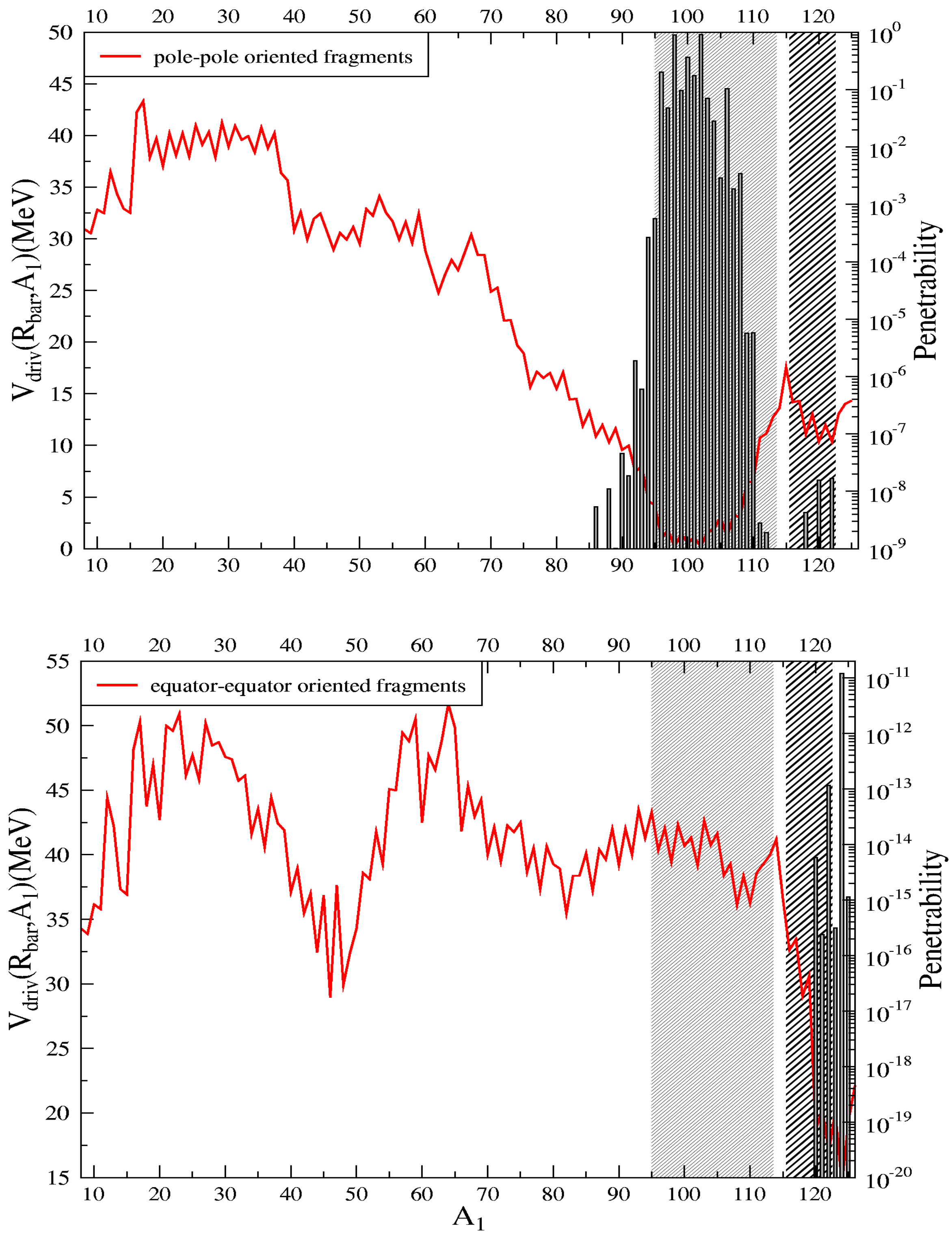
Ş.Mişicu&W.Greiner, PRC 69, 054601 (2004).



296 116
Quasi-fission
CN Fission
4He+ 292 112
14C+ 282 110
28Mg+ 268Rf
48Ca+ 248Cm
62Cr+ 234U
74Zn+ 222Rn
86Se+ 210Pb
90Kr+ 206Hg
100Zr+ 196Os
106Mo+ 190W
118Pd+ 178Yb
134Te+ 162Gd
140Xe+ 156Sm
148Ce+ 148Ce
nose-to-nose
belly-to-belly
crossed bellies
nose-to-belly
0
20
40
60
80
100
120
140
A1



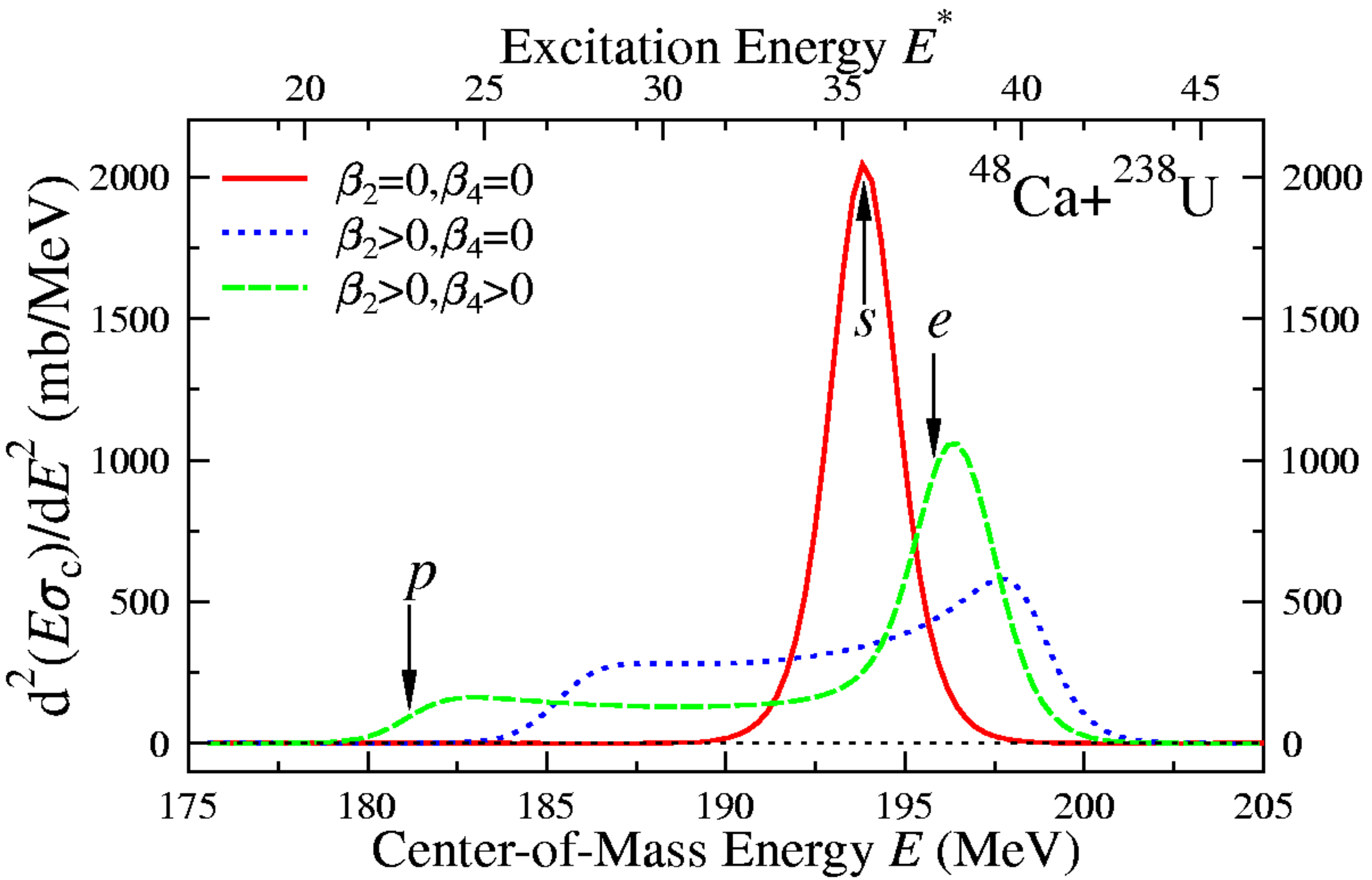
(a)
Ex = 33 MeV
248Cm + 48Ca
238U
FF
x20
QF
QF
132Sn
208Pb
Relative yield (%)
Fragment mass number
0
1
2
3
4
5
6
60
80
100
120
140
160
180
200
220
240


pole-pole oriented fragments
$V_{driv}(R_{bar},A_1)$(MeV)
Penetrability
equator-equator oriented fragments
$V_{driv}(R_{bar},A_1)$(MeV)
Penetrability
A_1

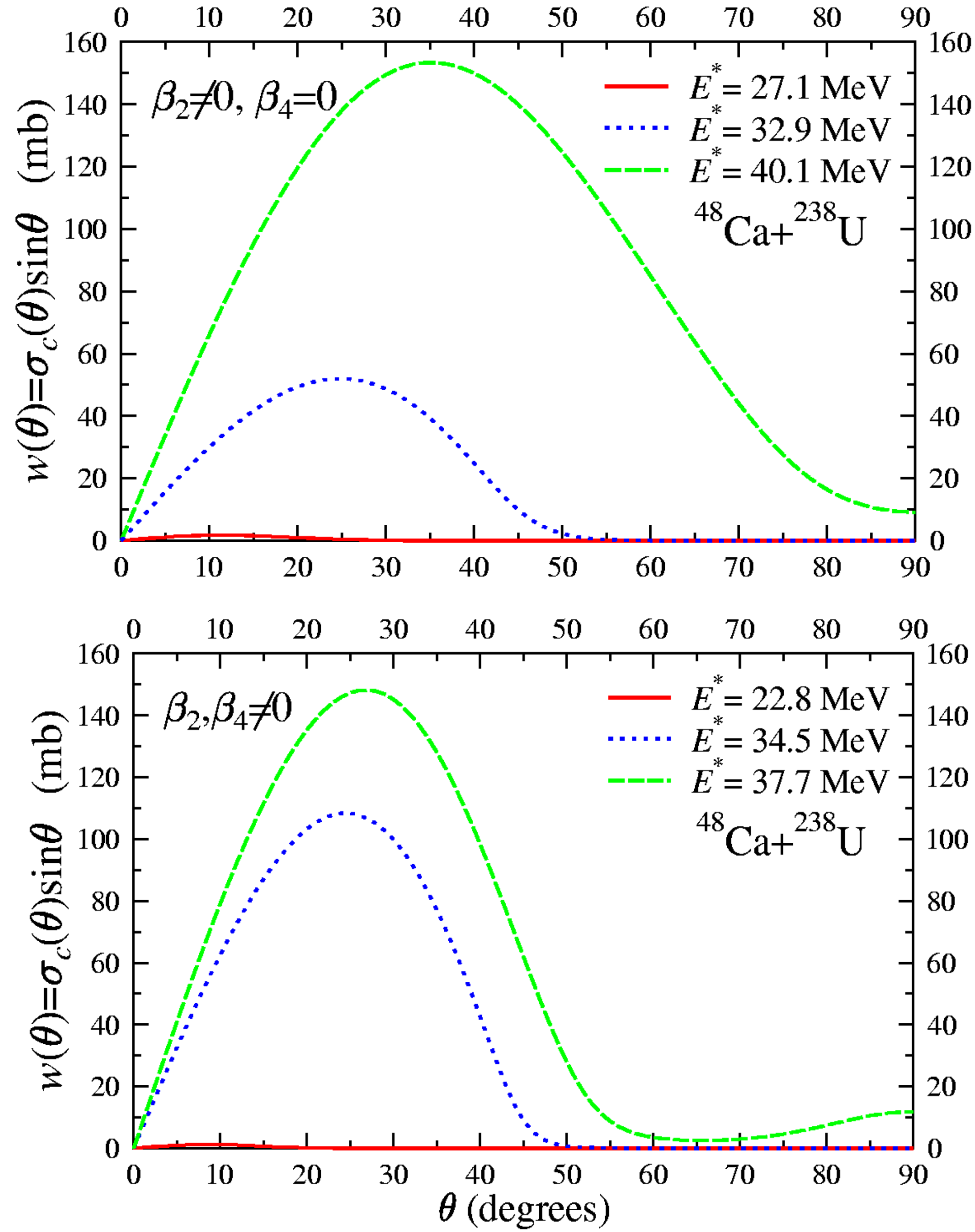
Barrier Distribution

$$D(E) = \frac{d^2(E\sigma_c)}{dE^2}$$

Probability to encounter a fusion barrier of height E



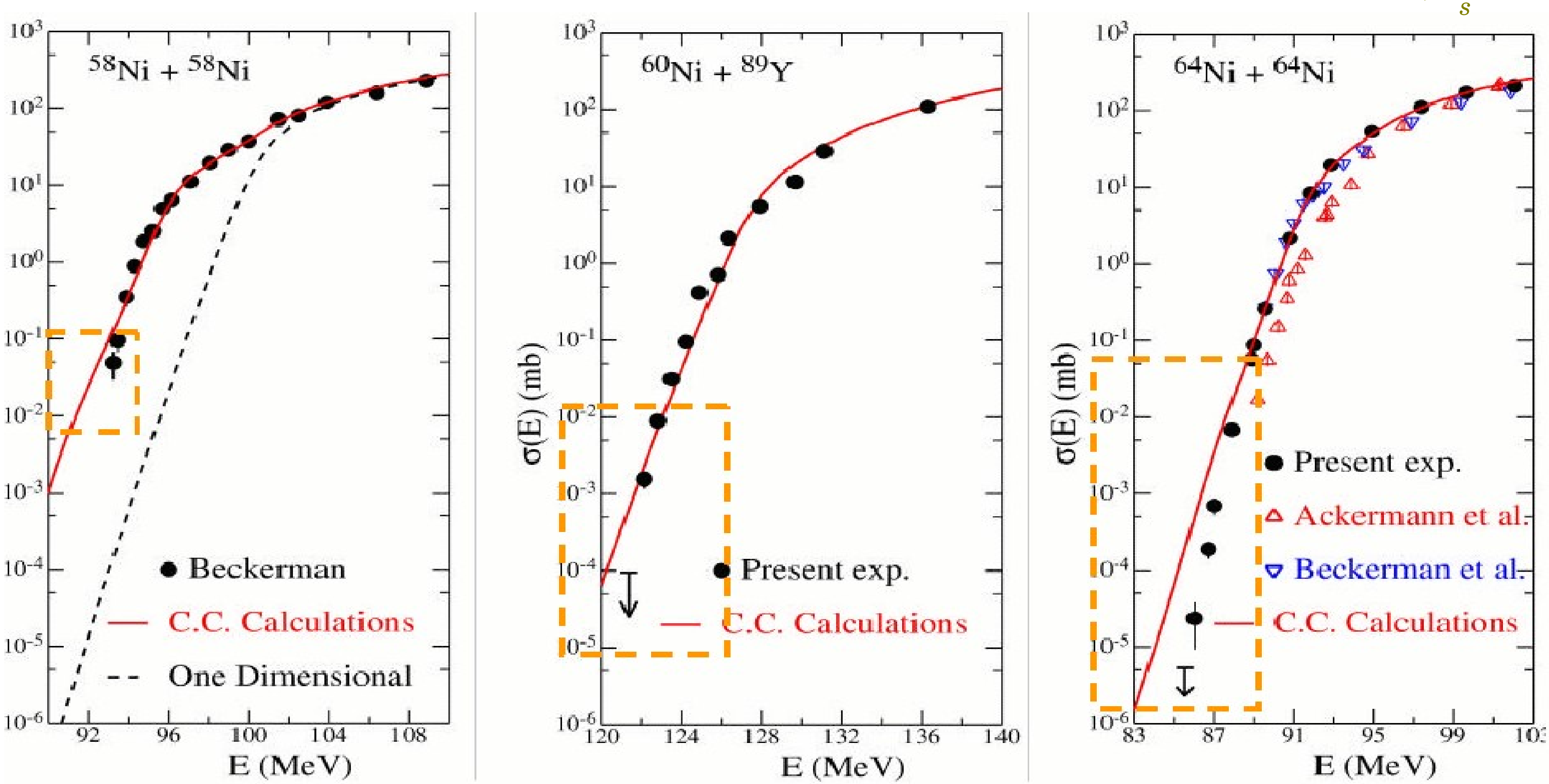
Effect of various Orientations



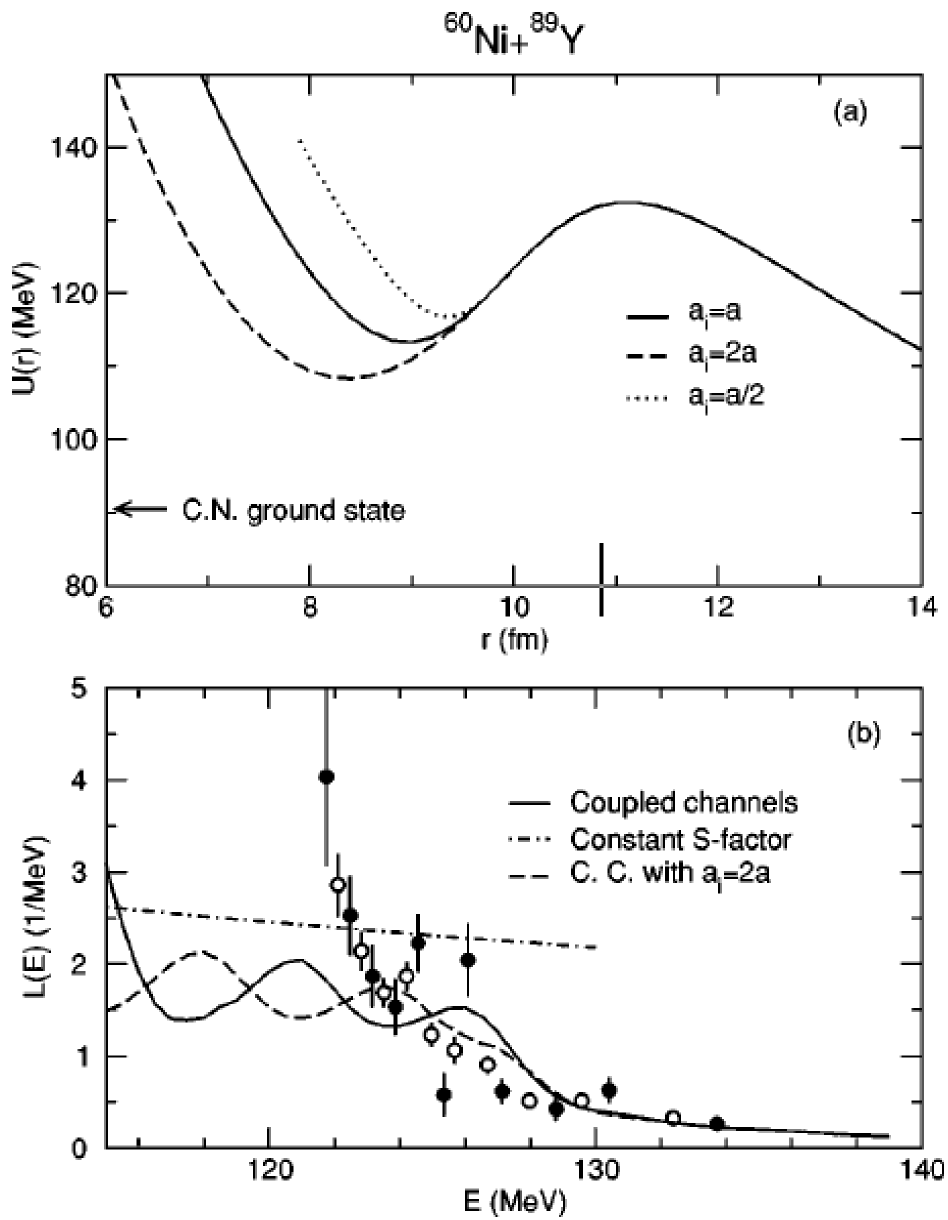
SUB-BARRIER FUSION : Hindrance for $E<E_s$

2001-Jiang conjectures that the hindrance of fusion far below the Coulomb barrier is a general phenomenon for many heavy-ion systems.

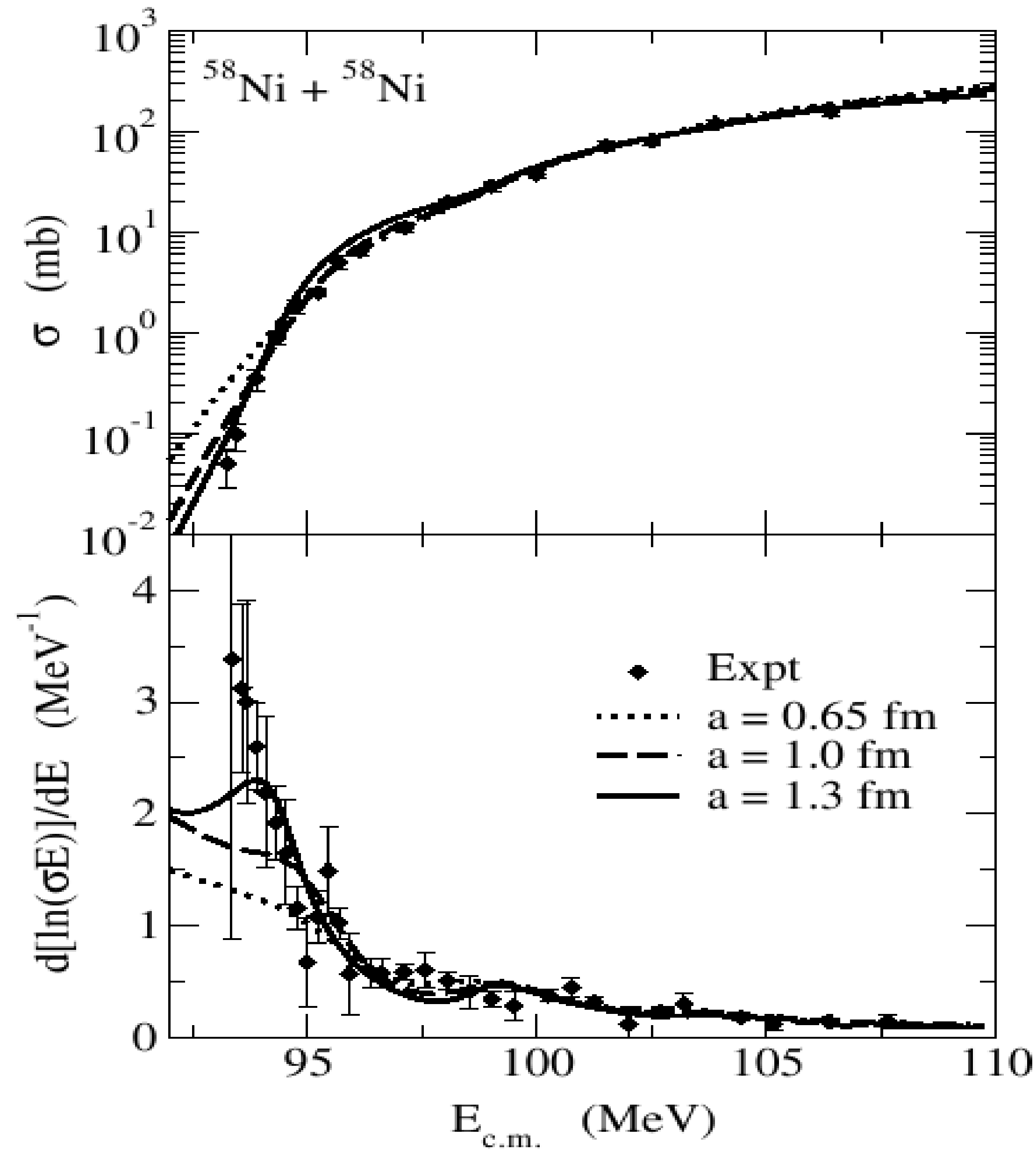
$E<E_s$



SUB-BARRIER FUSION : early attempts to solve the puzzle



C.L.Jiang et al. (PRC69,014604)



Hagino, Rowley and Dasgupta
(PRC 67, 054603 (2006))

Outgoing boundary conditions

$$u_n^{LM}(r) \longrightarrow \delta_{n0} F_L(k_n r) + T_n H_L^{(+)}(k_n r)$$

Transmission coefficient $$T_n = \frac{1}{2\pi}\left(\delta_{n0} - S_{n0}\right)$$

$$T = 1 - \sum_n |\, S_{n0}\,|^2 \quad \left(T = e^{-\frac{2}{\hbar}\int_{R_{t1}}^{R_{t2}} \sqrt{2\mu(E-V(r'))}dr'} \quad -WKB\right)$$

Cross section

$$\sigma_{\mathrm{F}}(E) = \frac{\pi}{k_0^2} \sum_L (2L+1) T_L$$

Repulsive Core

Calculate the cost of overlapping completely the ions from the EOS
Equate the cost to the (increase in HI potential)/particle

$$\Delta V \approx 2A_p \left[\varepsilon(2\rho_0, \delta) - \varepsilon(\rho_0, \delta)\right]$$

EOS – Thomas-Fermi Model (Myers&Swiatecki)

$$\varepsilon(\rho, \delta) = \varepsilon_F \left[A(\delta)\left(\frac{\rho}{\rho_0}\right)^{2/3} + B(\delta)\left(\frac{\rho}{\rho_0}\right) + C(\delta)\left(\frac{\rho}{\rho_0}\right)^{5/3}\right]$$

Incompressibility of Cold Nuclear Matter at saturation

$$K = 9\left(\rho^2 \frac{\partial^2 \varepsilon}{\partial \rho^2}\right)_{\rho=\rho_0}$$

Repulsive Core

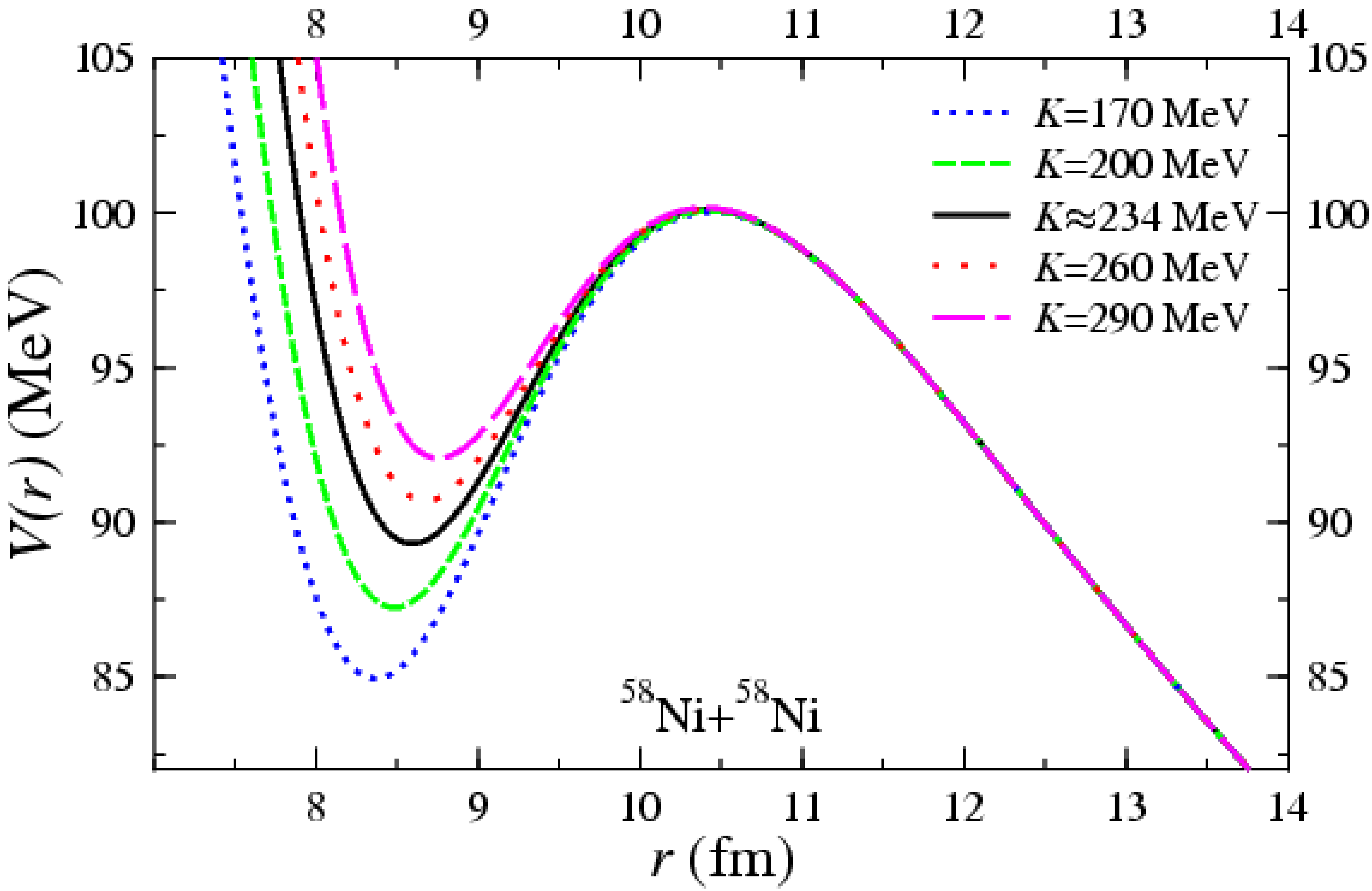
$$V_{\rm rep}(\boldsymbol{R}) = V_p \int d\boldsymbol{r}_1 \int d\boldsymbol{r}_2\ \widetilde{\rho}_1(\boldsymbol{r}_1)\widetilde{\rho}_2(\boldsymbol{r}_2)\delta(\boldsymbol{r}_{12})$$

Approximations to calibrate the strength of the repulsion

$$\varepsilon(\rho,\delta) = \varepsilon(\rho_0,\delta) + \frac{K}{18\rho_0^2}\ (\rho-\rho_0)^2$$

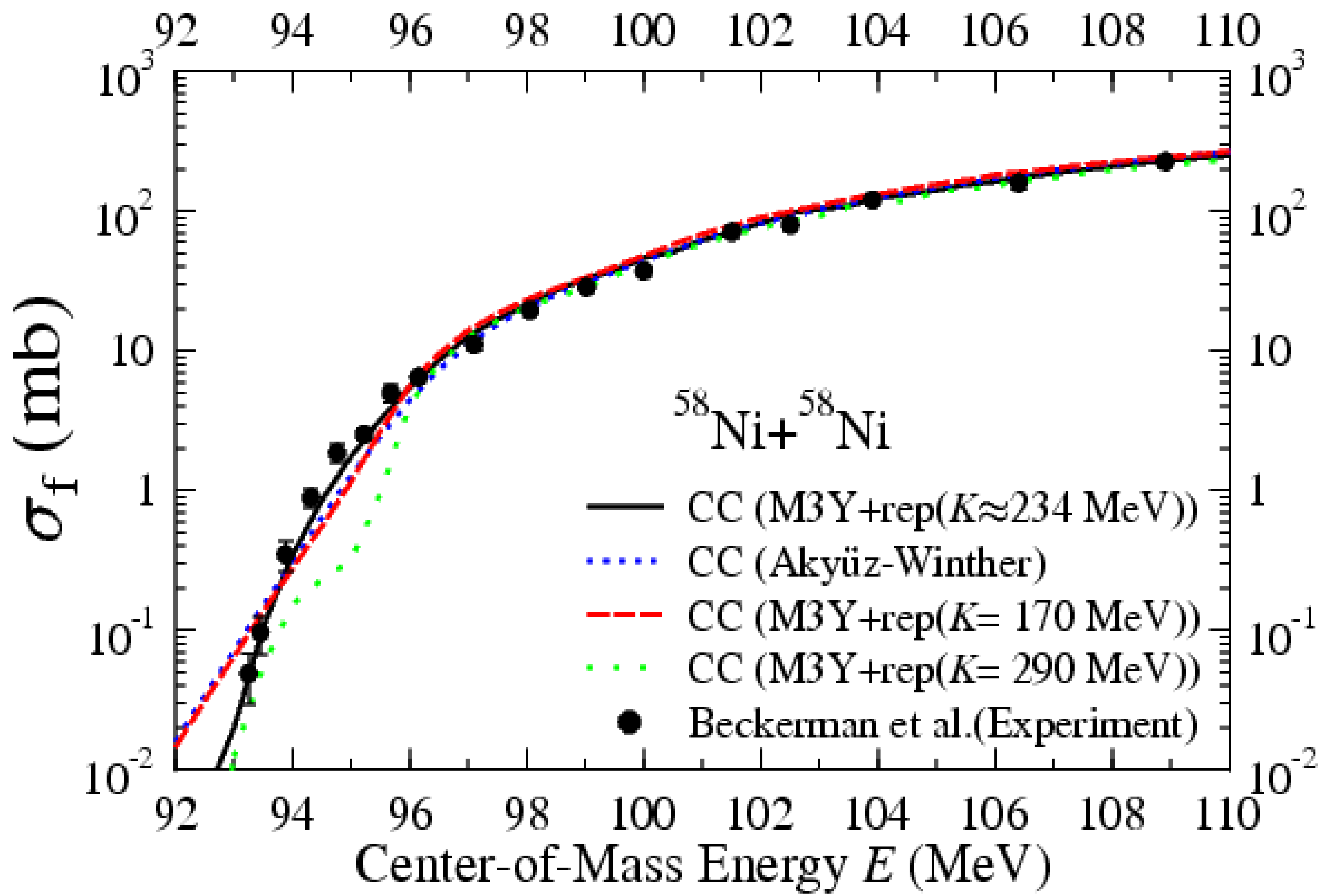
$$\Delta V = V_N(0)$$

Shallow potential



S.Misicu&H.Esbensen, PRC 75, 034606 (2007)

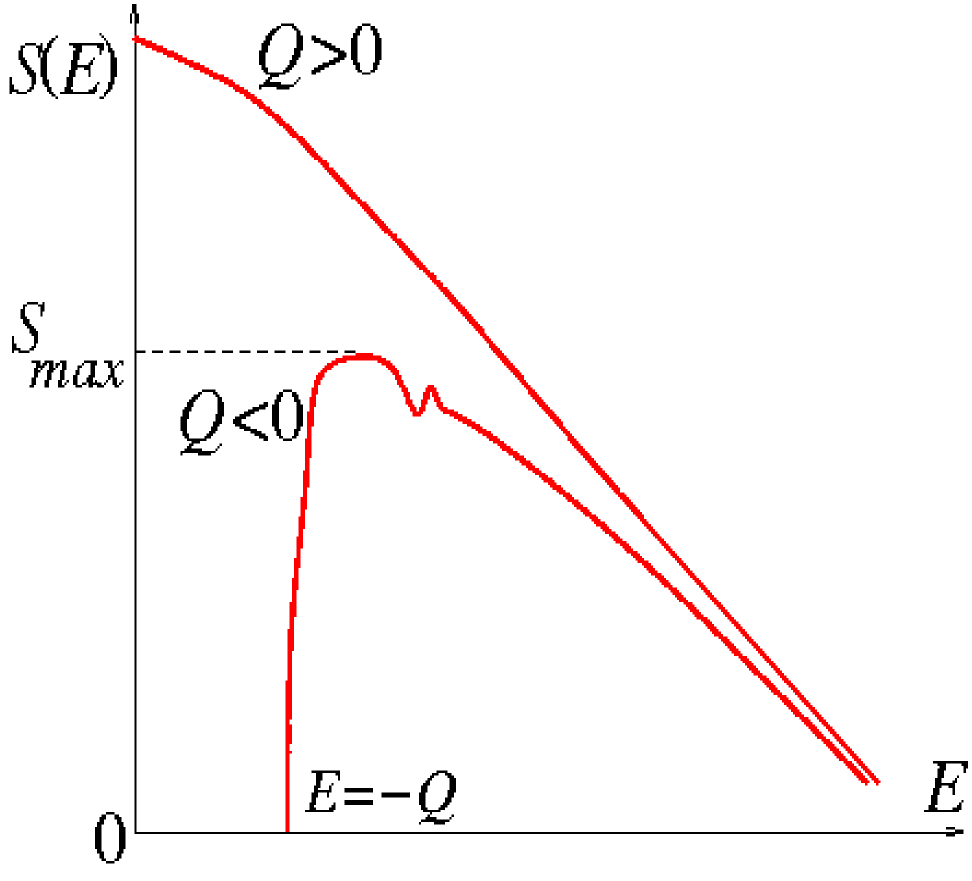
Fusion Cross-Sections vs. EOS



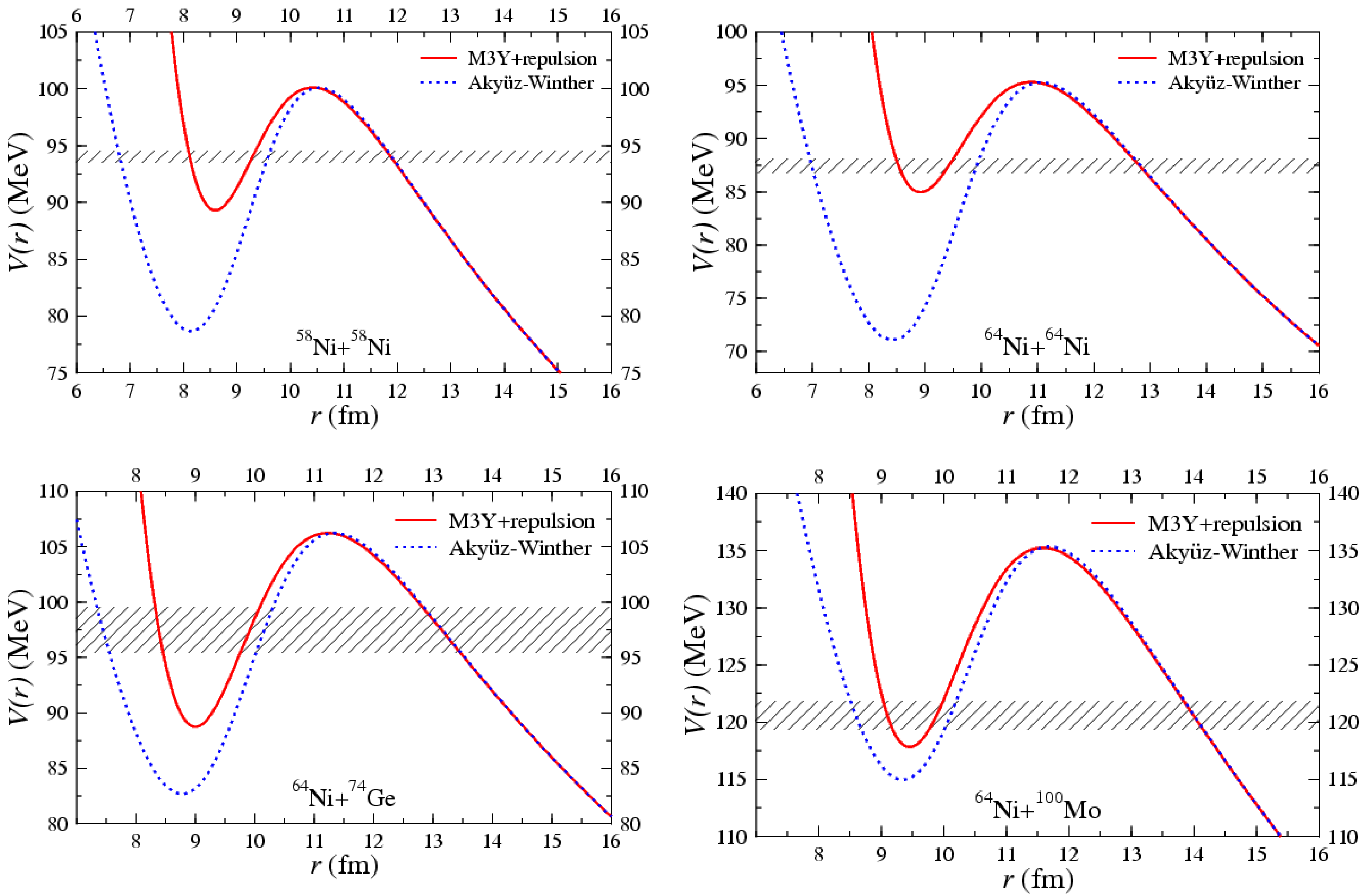
Diagnostic Tools: Astrophysical *S*-factor

$$S = E\sigma_F(E)\exp(2\pi\eta), \qquad \eta = \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 \hbar v}$$

- Magnify the low-energy behavior of cross-sections

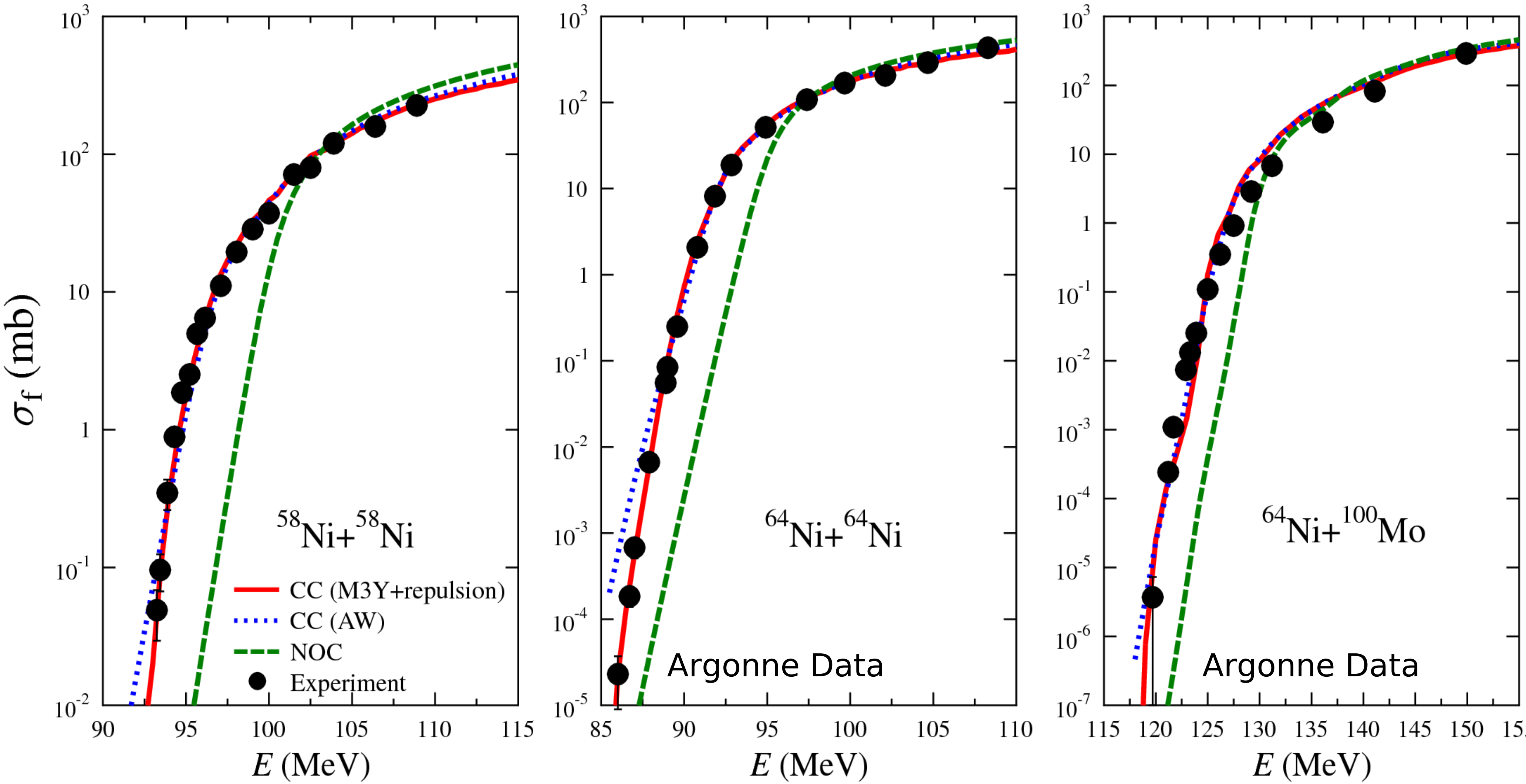


M3Y+repulsion vs.Woods-Saxon



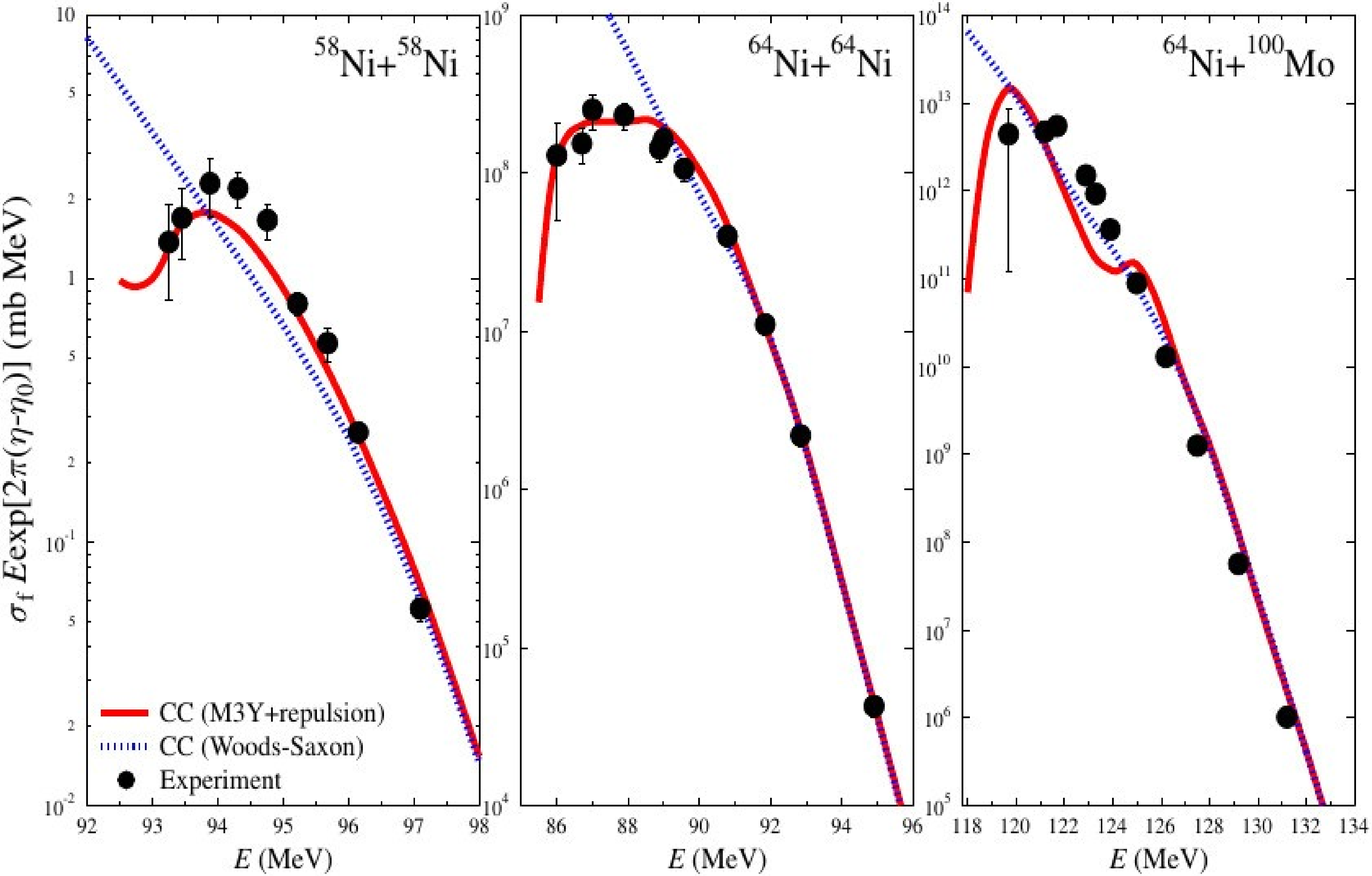
SUB-BARRIER FUSION : Maxium of S

^{58}Ni+^{58}Ni, Q=-66.12 MeV | ^{64}Ni+^{64}Ni, Q=-48.78 MeV | ^{64}Ni+^{100}Mo, Q=92.29 MeV

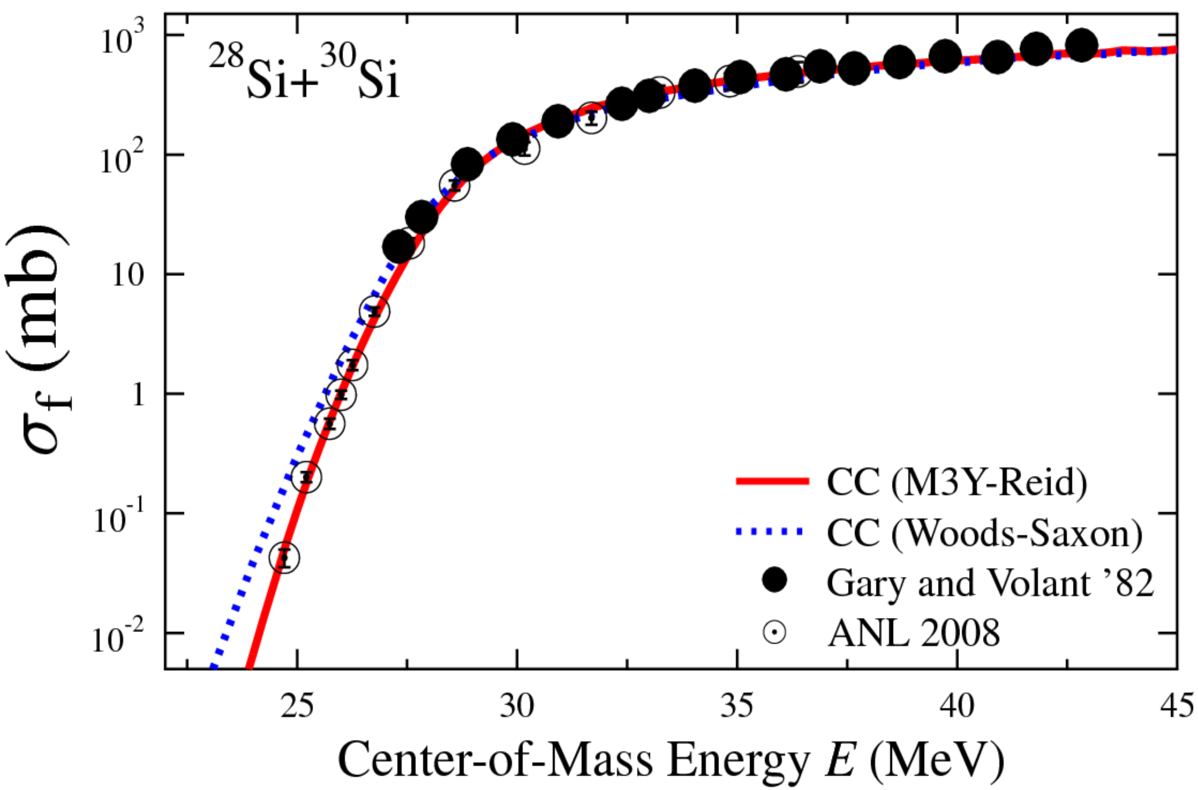


S.Misicu&H.Esbensen, PRL 96,112701(2006), PRC 75, 034606 (2007).

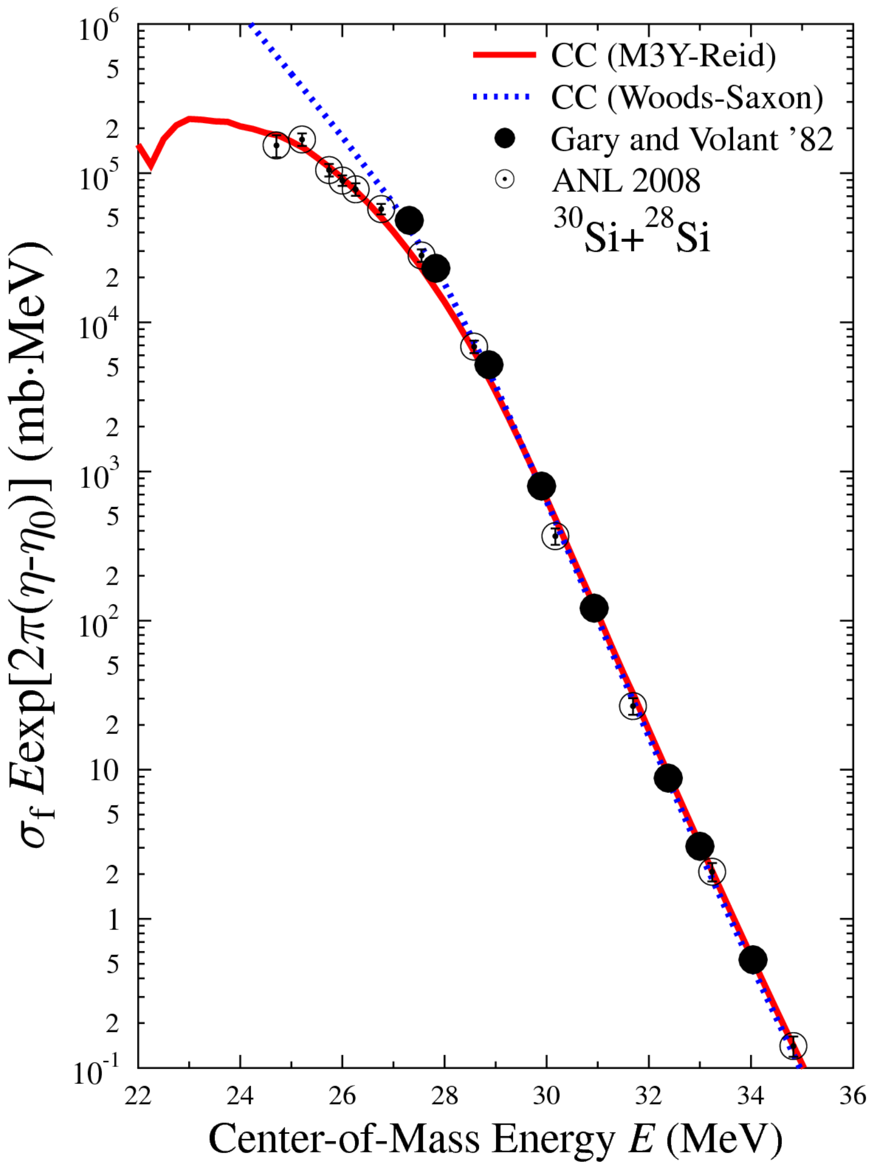
SUB-BARRIER FUSION : Maxium of S



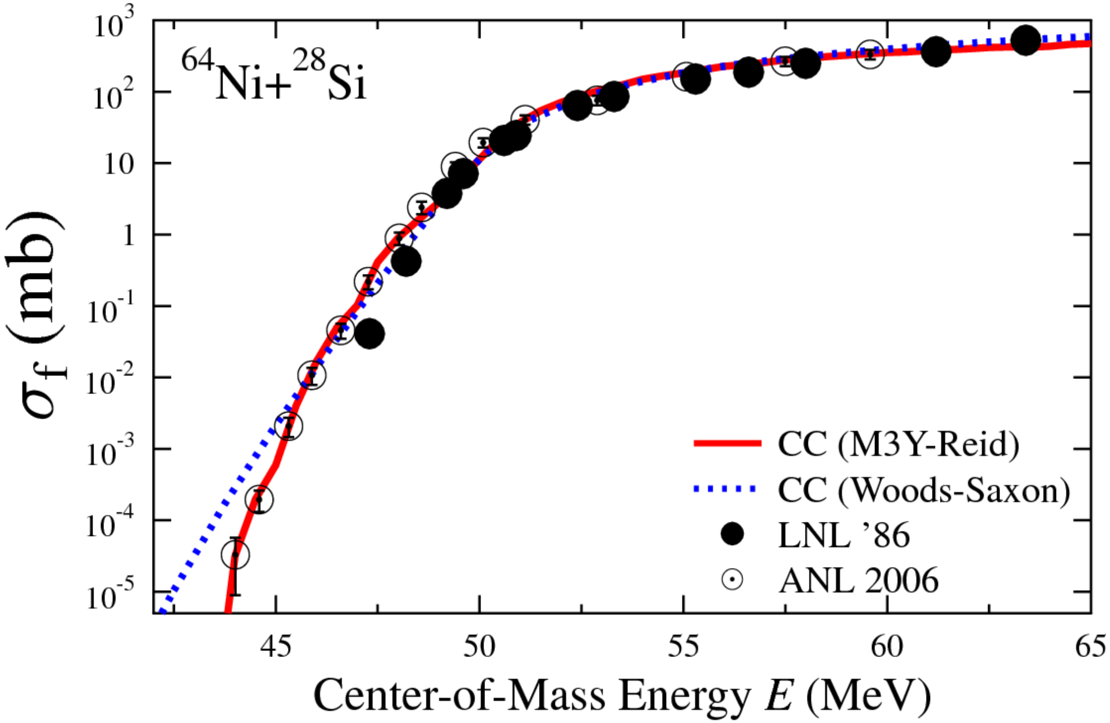
S.Misicu&H.Esbensen, PRL 96,112701(2006), PRC 75, 034606 (2007).



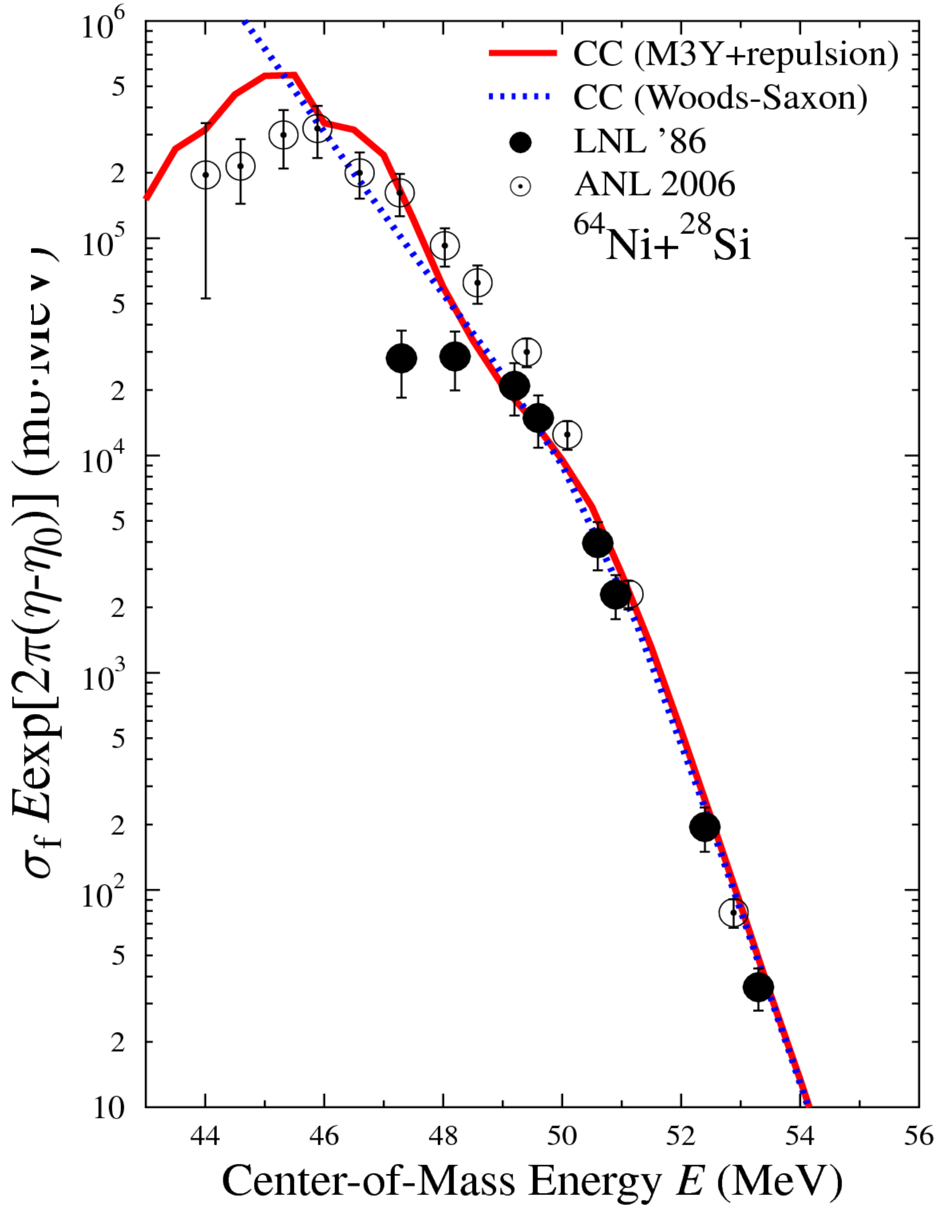
^{28}Si+^{30}Si
σ_f (mb)
Center-of-Mass Energy E (MeV)
CC (M3Y-Reid)
CC (Woods-Saxon)
Gary and Volant '82
ANL 2008



^{30}Si+^{28}Si
$\sigma_f\, E\exp[2\pi(\eta-\eta_0)]$ (mb·MeV)
Center-of-Mass Energy E (MeV)
CC (M3Y-Reid)
CC (Woods-Saxon)
Gary and Volant '82
ANL 2008

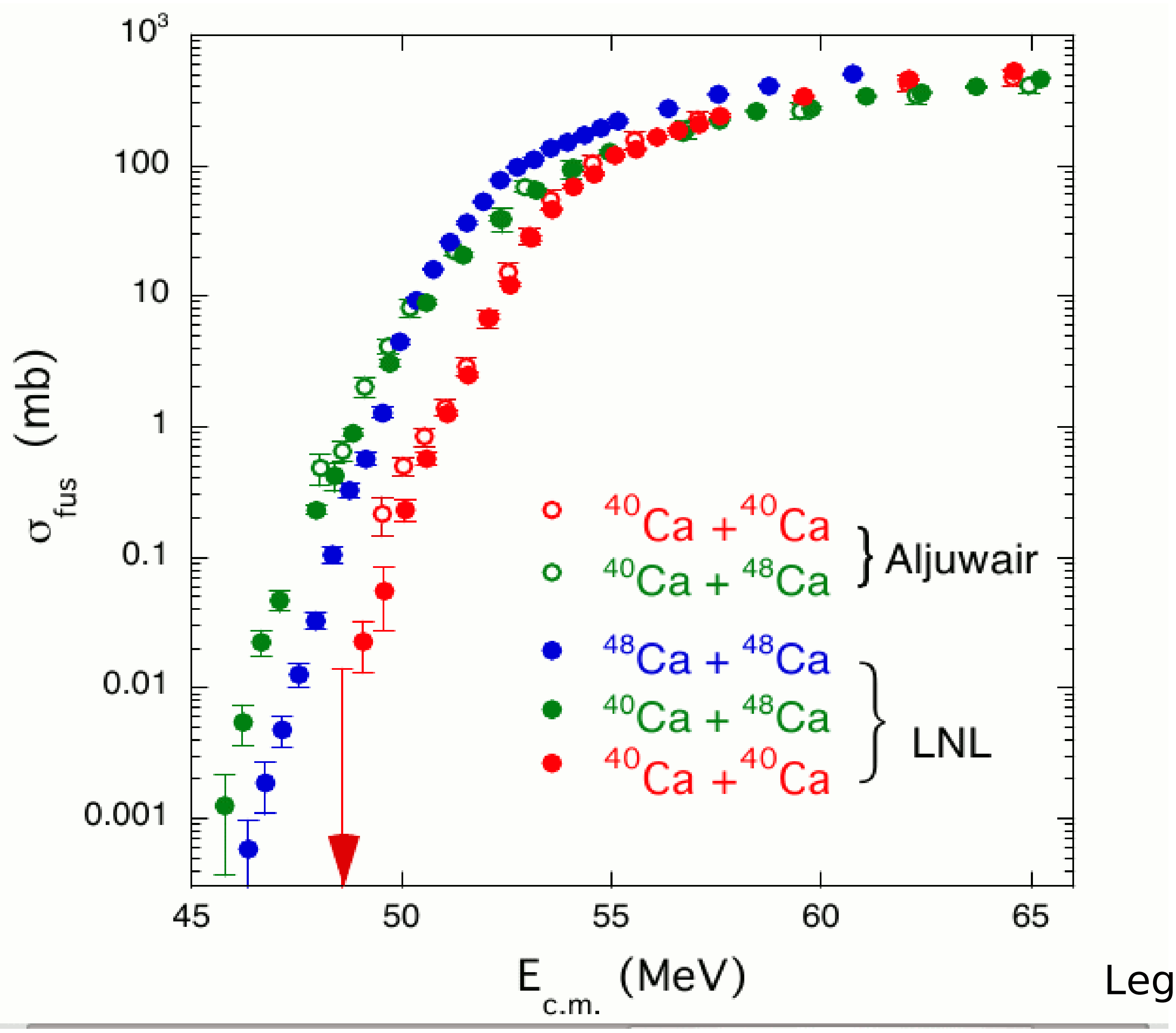


^{64}Ni+^{28}Si
CC (M3Y-Reid)
CC (Woods-Saxon)
LNL '86
ANL 2006
σ_f (mb)
Center-of-Mass Energy E (MeV)



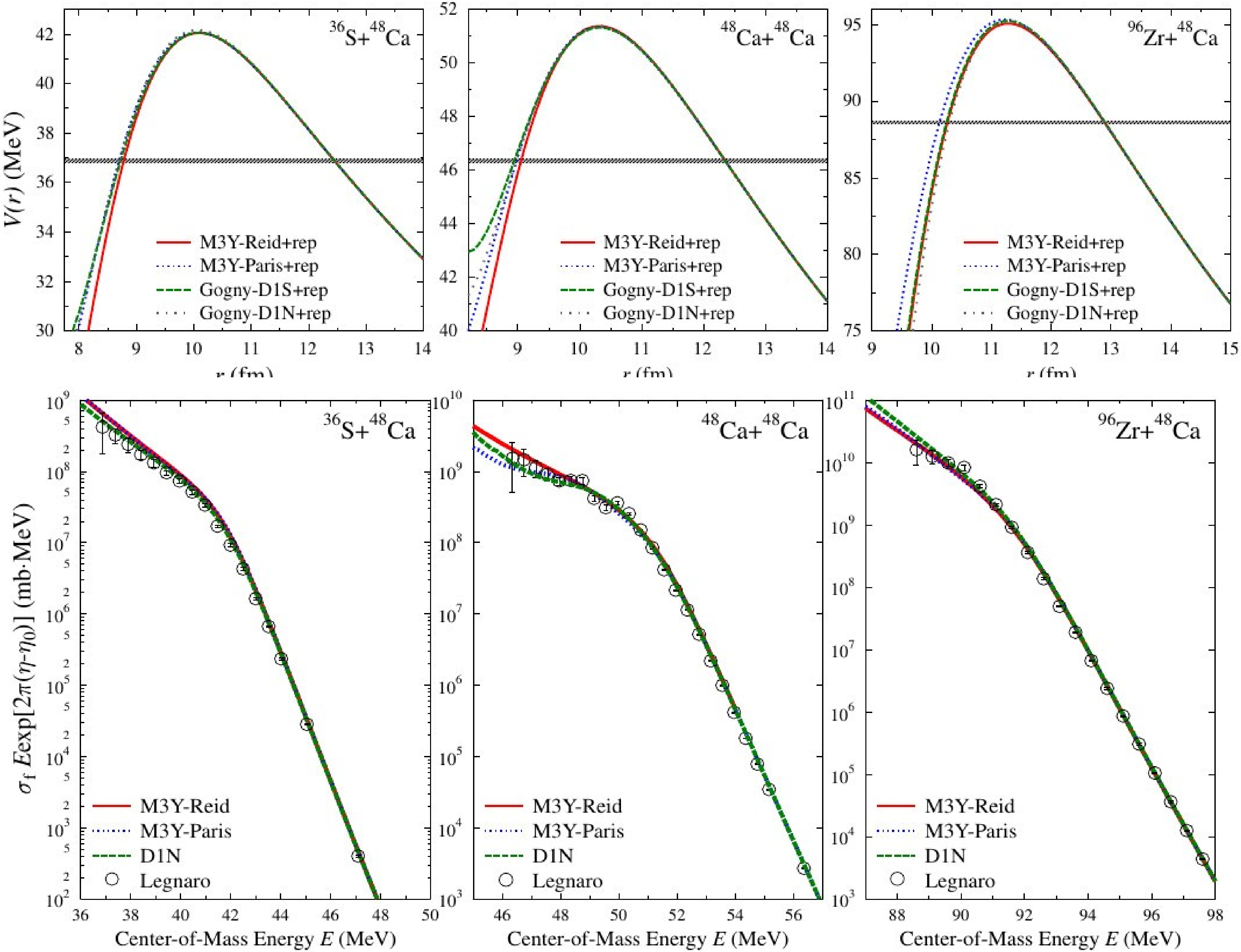
CC (M3Y+repulsion)
CC (Woods-Saxon)
LNL '86
ANL 2006
^{64}Ni+^{28}Si
$\sigma_f\, E\exp[2\pi(\eta-\eta_0)]$
Center-of-Mass Energy E (MeV)

SUB-BARRIER FUSION : Hindrance but no maxium of S

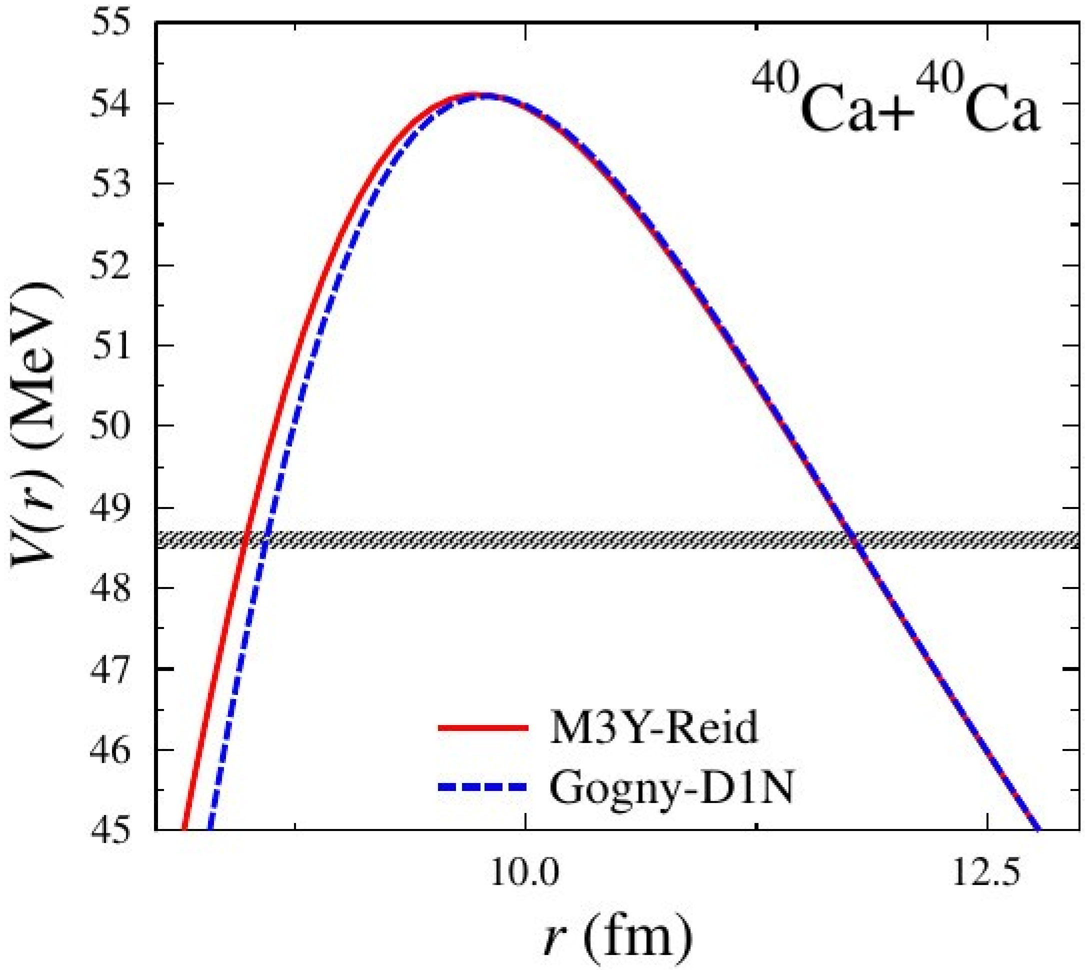


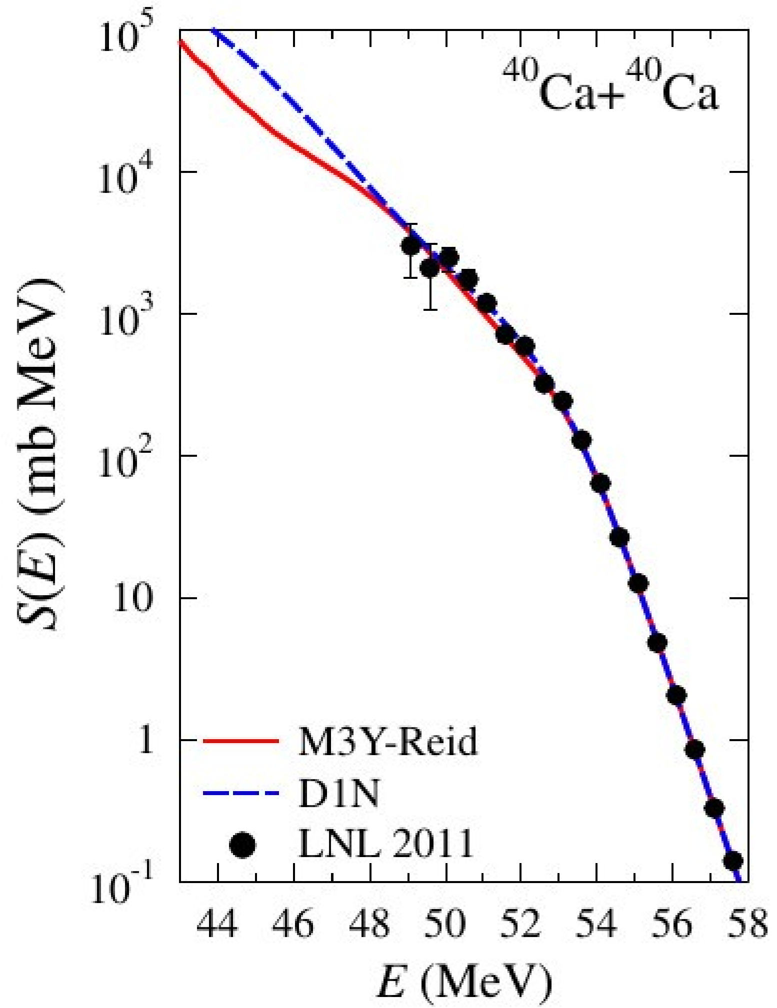
Legnaro (2009)

SUB-BARRIER FUSION : Hindrance but no maxium of S



SUB-BARRIER FUSION : Hindrance but no maxium of S

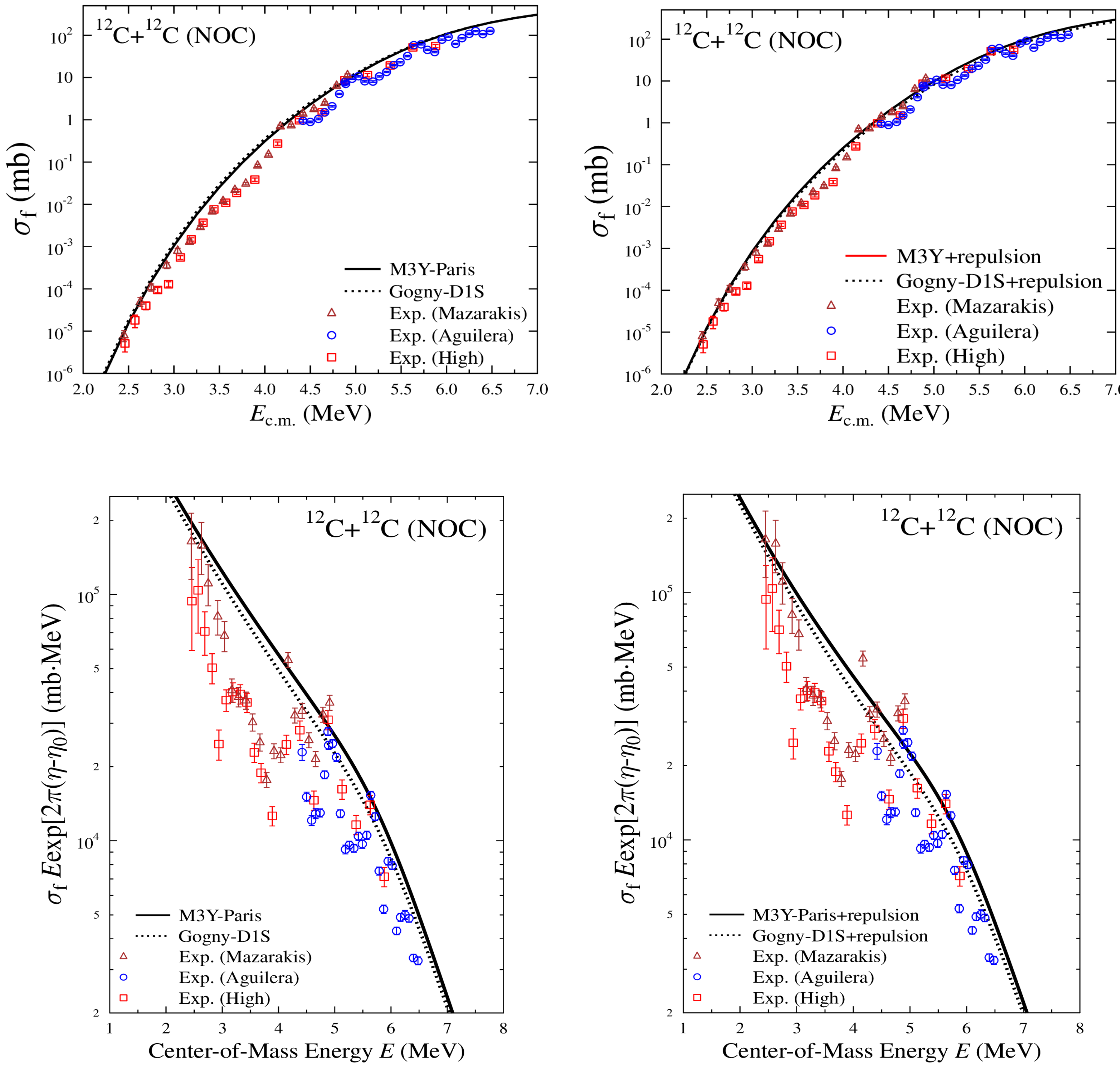




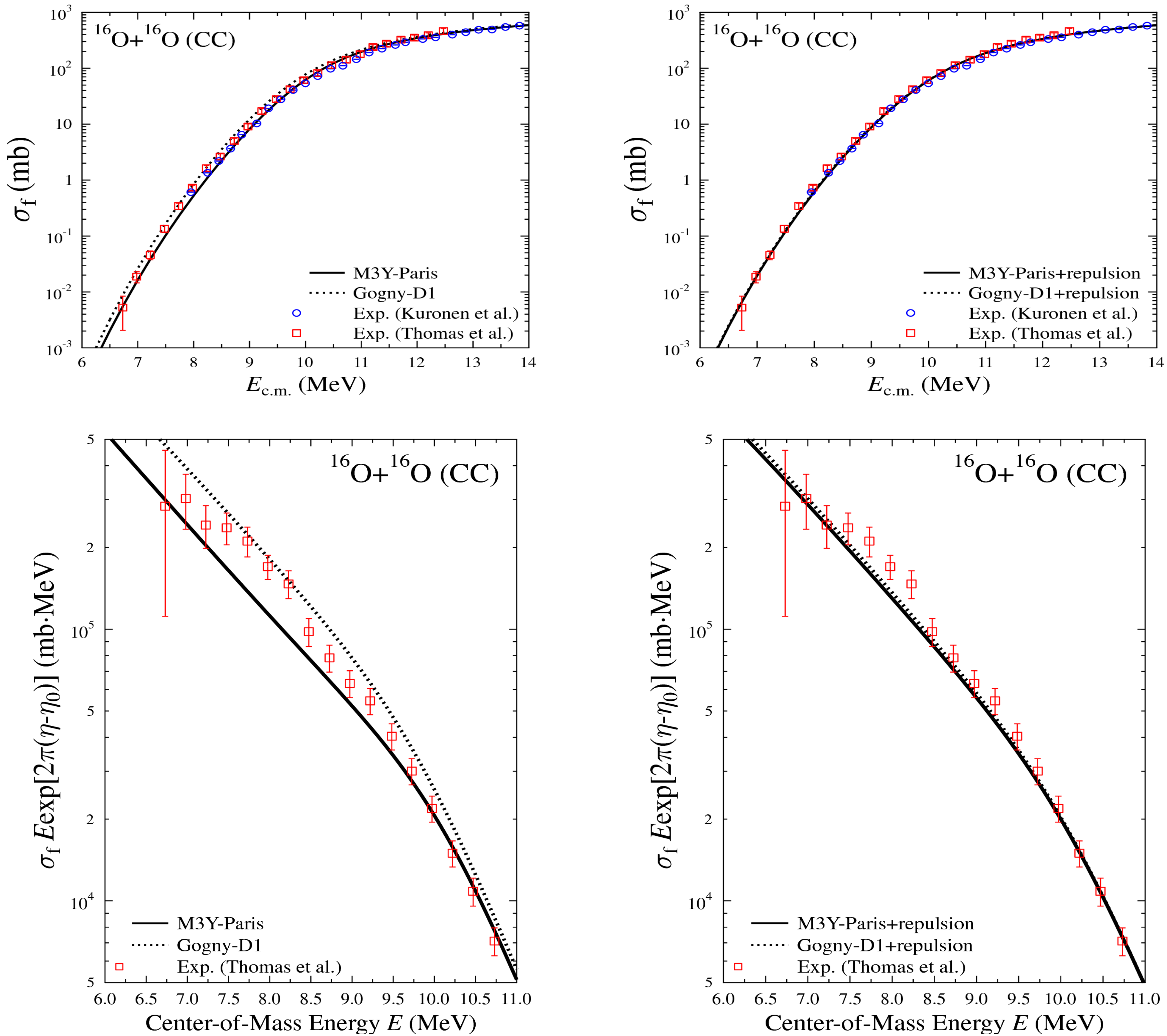
SUB-BARRIER FUSION : Lighter systems

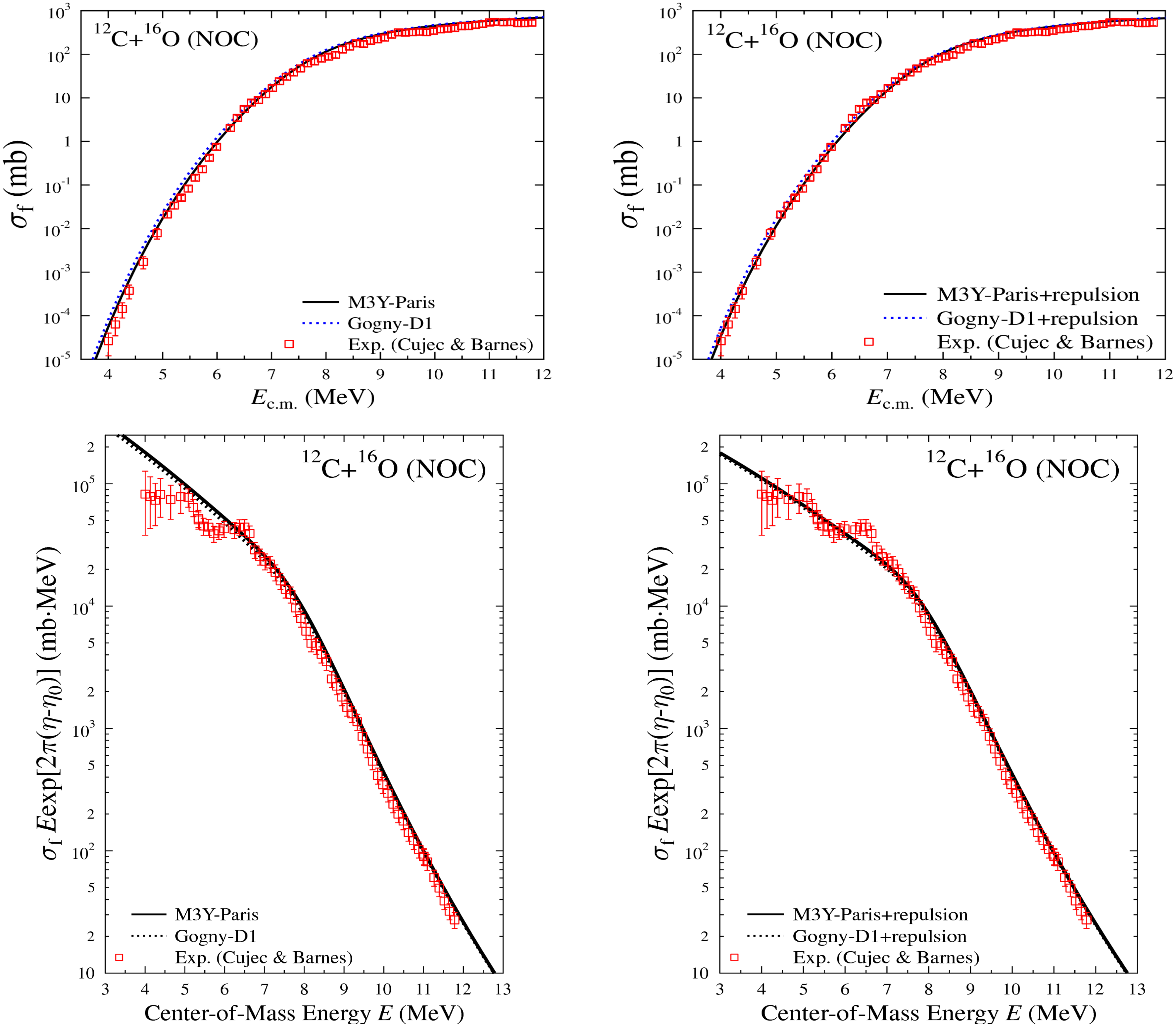
- WILL THE HINDRANCE PERSIST, and how will it affect the extrapolation to astrophysical reaction rates ?

YES!	**NO!**
Jiang et al. PRC 75, 015803, 2007	Misicu&Carstoiu, NPA 834, 180c(2010)
Gasques et al., PRC 76, 03582, 2007	



^{12}C+^{12}C (NOC)
σ_f (mb)
$E_{c.m.}$ (MeV)
M3Y-Paris
Gogny-D1S
Exp. (Mazarakis)
Exp. (Aguilera)
Exp. (High)
^{12}C+^{12}C (NOC)
σ_f (mb)
$E_{c.m.}$ (MeV)
M3Y+repulsion
Gogny-D1S+repulsion
Exp. (Mazarakis)
Exp. (Aguilera)
Exp. (High)
^{12}C+^{12}C (NOC)
$\sigma_f E\exp[2\pi(\eta-\eta_0)]$ (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris
Gogny-D1S
Exp. (Mazarakis)
Exp. (Aguilera)
Exp. (High)
^{12}C+^{12}C (NOC)
$\sigma_f E\exp[2\pi(\eta-\eta_0)]$ (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris+repulsion
Gogny-D1S+repulsion
Exp. (Mazarakis)
Exp. (Aguilera)
Exp. (High)


^{16}O+^{16}O (CC)
σ_f (mb)
$E_{c.m.}$ (MeV)
M3Y-Paris
Gogny-D1
Exp. (Kuronen et al.)
Exp. (Thomas et al.)
^{16}O+^{16}O (CC)
σ_f (mb)
$E_{c.m.}$ (MeV)
M3Y-Paris+repulsion
Gogny-D1+repulsion
Exp. (Kuronen et al.)
Exp. (Thomas et al.)
^{16}O+^{16}O (CC)
$\sigma_f E\exp[2\pi(\eta-\eta_0)]$ (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris
Gogny-D1
Exp. (Thomas et al.)
^{16}O+^{16}O (CC)
$\sigma_f E\exp[2\pi(\eta-\eta_0)]$ (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris+repulsion
Gogny-D1+repulsion
Exp. (Thomas et al.)



12C+16O (NOC)
σf (mb)
Ecm (MeV)
M3Y-Paris
Gogny-D1
Exp. (Cujec & Barnes)
12C+16O (NOC)
σf (mb)
Ecm (MeV)
M3Y-Paris+repulsion
Gogny-D1+repulsion
Exp. (Cujec & Barnes)
12C+16O (NOC)
σf Eexp[2π(η-η0)] (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris
Gogny-D1
Exp. (Cujec & Barnes)
12C+16O (NOC)
σf Eexp[2π(η-η0)] (mb·MeV)
Center-of-Mass Energy E (MeV)
M3Y-Paris+repulsion
Gogny-D1+repulsion
Exp. (Cujec & Barnes)

Acknowledgements

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